# Human Subsystem Working Group
# Human Planning Guidelines and Constraints

September 5, 2001

## Contents

## Objectives (RKF)

Identify the points of intersection between humans and exploration mission considerations such as architecture, vehicle design, technologies, operations and science requirements. This information is intended to be a clear and common source of top level guidelines for human related exploration studies and technology research.

## Scope (RKF)

This document is envisioned as an executive summary of existing information in Manned Systems Integration Standards (MSIS), BioAstronautics Data Book, Critical Path Roadmap, Moon/Mars Ops Constraints, Advanced EVA Requirements and other appropriate sources. The topics of interest have significant influences upon time, mass, volume, power, risk and cost. Parameters that vary due to unique environments of different destinations are addressed. For topics without conclusive parameters, best/worst case boundary condition, TBD's or other caveats are listed. When warranted by uncertainties, the pros/cons and parameters of possible resolution approaches are discussed. This document is provided as a focused collection of the key drivers upon human system designs. It can help ensure that ongoing mission trade studies address common, standard and practical criteria for human interfaces.

## 1.0 Ground Rules and Assumptions (RKF)

Exploration implementation must be cost effective, safe and efficiently productive if is it to address the goals of the many possible destinations and applications. A major motivator for current exploration studies is the growing acknowledgement that automation alone cannot accomplish the desired scientific objectives within a reasonable time period and without direct human intervention. Unfortunately, typical space rated human systems tend to be prohibitively expensive and unable to safely support significant durations beyond LEO. The premise of current thinking is that safe and affordable human systems are feasible and can work in concert with automated systems to accomplish the desired objectives faster than a long series of purely robotic missions. While standalone automated means are appropriate for selected applications, the addition of the following human capabilities provides leverage to enable otherwise difficult or impossible ventures.

**Productivity** - Use of the brain's creative cognitive abilities enables rapid on-scene decisions which overcome time delays and data bandwidth limits.
**Reliability** – Adaptive and proven capability for manual response to unforeseen, unique and non-repetitive activities
**Cost/Mass** – Less need to expend resources upon complex, redundant and fully automated designs

For this document, these boundary conditions upon human exploration systems are assumed.

- Timeframe : 10 years (near earth) and 20 years (Mars)
- Remote Destinations : L1 Libration Point, Moon, Mars
- Mission Duration : 50-100 days or 500-1000 days
- Transport Durations : 5-10 days (near earth) and 90-180 days (Mars)
- Transport Cargo Frequency : monthly (near earth) and biannual (Mars)
- Human/Robot Options : Standalone, Cooperative, Local/Remote Telepresence (see below)
- Tasks : Planetary/Astronomical Science, Assembly, Maintenance, Contingencies, Commerce
- Primary Safety Criteria : Near zero risk to public on earth
- Mission Safety Criteria : Return all crew alive without serious injury or illness
- Assembly/Maint Success Criteria : Spacecraft stable and viable for productive work
- Science Success Criteria : Majority of tasks completed
- Overall Success Criteria : No major impediment to subsequent missions
- Budget : Generally flat across the agency for the foreseeable future
- Mass, volume and power : Finite with severely constrained delivery
- International Participation : Not to be precluded

### Exploration Implementation Options

The options and impacts of possible human and robotic roles are diverse :

| Robot Method | Human Role | Site Access | Data Scope | Rel Cost | Hdw Repair | Safety Risk |
|---|---|---|---|---|---|---|
| Remote teleoperation | Earth based control | Lowest | Lowest | Low | None | None |
| Fully automated | Earth based monitoring | Low | Low | Low-Med | None | None |
| Local teleoperation | Orbital habitat | Low | Low-Med | Med | None | Low |
| Local teleoperation | Lander habitat-No EVA | Low | Low-Med | Med-Hi | None | High |
| Variable autonomy | Lander habitat-No EVA | Low | Med | Med-Hi | None | High |
| Variable autonomy (pressurized garage) | Lander habitat-No EVA | Low | Med | Med-Hi | Partial | High |
| Variable autonomy (dockable to habitat) | Canned mobility (No EVA Capability) | Low-Med | Med | High | Partial | Highest |
| Precursors only | Suited humans on foot | Med-Hi | High | Med-Hi | Full | Med |
| Variable autonomy (total crew access) | Suited transportable humans (w/Rovers) | Highest | Highest | Highest | Full | Med-Hi |

## 2.0 Priorities and Risk Tolerance (J. Charles and J. Railsback)

Any long-duration exploration mission beyond earth orbit will confront risks at every stage of its life cycle, including the period before it is launched. In addition to the physical risks to the crew and to the vehicle, there is the "cost risk" due to excessive expenditures or inadequate funding, and the "programmatic risk" of political as well as technical limitations on the mission itself and on the program that sponsors it and future missions.

For the purposes of this analysis, risk is defined in terms of "harm" and "hazard." "Harm, hurt, injury, damage, or loss of functionality" is simply the occurrence of an undesirable event or condition and the consequence of that event or condition; "hazard" is exposure to possible "harm"; and "risk" is the probability of a "hazard" actually resulting in "harm."

**Mission Success**

A risk is frequently expressed as a threat to success. Mission Assurance is a process for assuring that a mission achieves success by performing properly. Attention is required during the requirements definition, design, manufacture, operation, and maintenance phases – all of which must be integrated for the mission to succeed. Mission success also requires the institution of hardware certification requirements: the project must certify hardware and software by test, analysis, or (preferably) both.

Mission success may be defined as the return to earth of the human crew in good health from a mission including thorough and well-documented *in situ* field studies and analysis, return of selected specimens or data, and adequate and appropriate public outreach activities.

Mission success requires consideration of factors beyond the mission itself. NASA has established an overarching priority order for risk mitigation expressed as safety in all of its undertakings, including crewed exploration missions:

- First, **safety for the public**, which must not be injured due to mission architecture, operations and procedures, including (but not limited to): launch phase malfunctions; the return to earth of hazardous materials (such as nuclear power sources or extra-planetary specimens; mis-operation disasters (such as "shoot-downward" of unsafe beams or trajectories of objects, communications disruptions, etc.); and longer term consequences of mishaps (pollution, environmental damage, etc).
- Second, **safety for astronauts and pilots**, who are exposed to risk in high hazard flight regimes.
- Third, **safety for employees**, to ensure a safe and healthful workplace to provide the infrastructure and resources for the mission.
- Fourth, **safety for high value equipment**, as an investment by the public in mission activities.

Implicit in this hierarchy is the subsidiary importance of mission goals (such as science return) compared to the safety of people and equipment. Within the mission itself, priority decreases from protecting the crew, to protecting the vehicle, then to protecting the payload, with the understanding that these are overlapping constraints and may not be clear and distinct.

**Biomedical Risk Management**

Foremost among the issues confronting a crewed exploration mission are the biomedical and life support risks incurred by exposing astronauts to the space flight environment. The biomedical and life support risks of exploration missions have been defined through the Bioastronautics Critical Path Roadmap, a strategic plan for reducing risks to human health and safety during long duration space flight. It provides:

- a guide for prioritization of research and technology initiatives directed at this goal;

- a framework for assessment of progress toward mitigating specific risks by assessing their countermeasure and technical readiness levels;
- a way to track effective risk mitigation strategies for all of the risks it identifies, to removed risks as they are mitigated, and to add any new risks that are identified;
- a way to determine acceptable levels for identified risks.

Critical risks were identified for each discipline area as well as a set of core critical questions. Currently there are 55 critical risks and 343 critical questions. They are being addressed though research funded by NASA Office of Biological and Physical Research (Code U) and by the National Space Biomedical Research Institute (NSBRI).

Vehicle Design Requirements

Foremost among the items of equipment required for mission success is the vehicle or vehicles that will transport the crew and assure their safety, health and efficient function. Requirements for such vehicles (as documented in JSC 28354, NASA Human Rating Requirements, June 1998) are the following: [1]

General Requirements

1. The vehicle shall be designed, built, inspected, tested, and certified specifically addressing the requirements for human-rating.
2. The vehicle design, manufacture, and test shall comply with JSCM 8080.5 and applicable military standards. Where alternative approaches are employed, verification shall be provided that the alternative approaches meet or exceed the performance of accepted approaches.
3. The vehicle crew habitability and life support systems shall comply with NASA Standard 3000 and NASA Space Flight Health Requirements for crew habitability and life support systems design.
4. A successful, comprehensive flight test program shall be completed to validate analytical math models, verify the safe flight envelope, and provide a performance database prior to the first operational flight (flights other than for the specific purpose of flight test) with humans on board.
5. Spacecraft operations in proximity or docking with a crewed vehicle shall comply with joint vehicle and operational requirements so as to not pose a hazard to either vehicle. Provisions shall be made to enable abort, breakout, and separation by either vehicle without violating the design and operational requirements of either vehicle. Uncrewed vehicles must permit safety critical commanding from the crewed vehicle.

Safety and Reliability Requirements

6. The program shall be designed so that the cumulative probability of safe crew return over the life of the program exceeds 0.99. This will be accomplished through the use of all available mechanisms including mission success, abort, safe haven, and crew escape
7. A crew escape system shall be provided on *future (e.g., post-Space Shuttle)* earth-to-orbit (ETO) vehicles for safe crew extraction and recovery from in-flight failures across the flight envelope from prelaunch to landing. The escape system shall have a probability of successful crew return of 0.99. ***This should grandfather Shuttle. Our current approach for Earth's Neighborhoodis to use existing launch vehicles.***
8. For ETO vehicles, abort modes shall be provided for all phases of flight to safely recover the crew and vehicle or permit the use of the crew escape system. For beyond-earth orbit (BEO) missions, spacecraft and propulsion systems shall have sufficient power to fly trajectories with abort capabilities and provide power and critical consumables for crew survival. Trajectories and propulsion systems shall be optimized to provide abort options. When such options are unavailable, safe haven capabilities shall be provided.
9. If a flight termination (range safety) system is required for *future (e.g., post-Space Shuttle)* ETO vehicles, the vehicle design shall provide for safe recovery of the crew. ***This should***

[1] Italicized text added by JBC, and is not present in JSC 28354.

***grandfather Shuttle. Our current approach for Earth's Neighborhoodis to use existing launch vehicles.***

10. All critical systems essential for crew safety shall be designed to be two-fault tolerant. When this is not practical, systems shall be designed so that no single failure shall cause loss of the crew. For the purposes of this requirement, maintenance can be considered as the third leg of redundancy so long as mission operations and logistics resupply permit it.
11. Vehicle reliability shall be verified by test backed up with analysis at the integrated system level prior to the first flight with humans on board and verified by flight-based analysis and system health monitoring for each subsequent flight.
12. The performance and reliability of all critical software shall be tested on a flight equivalent avionics testbed across the entire flight envelope. Independent Verification and Validation (IV&V) methods shall be used to confirm the integrity of the software testing process

Human-in-the-Loop Requirements

13. The vehicle shall provide the flight crew on board the vehicle with proper insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and critical autonomy from the ground.
14. The flight crew shall be capable of taking manual control of the vehicle during all phases of flight. The vehicle shall exhibit Level I handling qualities as defined by the Cooper-Harper Rating Scale.
15. The spacecraft displays and controls design shall be based on a detailed function and task analysis performed by an integrated team of human factors engineers with spacecraft displays and controls design experience, vehicle engineers, and crew members. *Solutions in this design area shall not be limited to those derived from experience with Shuttle if newer or alternative concepts are applicable.*
16. The mission design, including task design and scheduling, shall not adversely impact the ability of the crew to operate the vehicle.

**Risk Management**

A mission must identify potential risks to the crew, the vehicle and the payload early in the design process by comparing candidate mission architectures, operations, elements, and equipment design concepts to determine the optimal relation between system performance and risk minimization with adequate margins of safety. The Continuous Risk Management Plan (described in NPG 7120.5A) provides a method that:

- Identifies risks
- Analyzes their impact and ranks them
- Plans for risk mitigation, or acceptance
- Tracks the implementation of mitigation plans
- Controls risks and mitigation plans
- Communicates the risks to management.

The Continuous Risk Management process begins in the formulation phase with an initial risk identification and development of a Risk Management Plan, and continues throughout the project's life cycle through the disposition and tracking of existing and new risks. As candidate missions are developed, the differences in their risks lead to informed decisions regarding mission architecture and system configurations. The Risk Management Plan also provides a step-by-step description of how a risk is identified, analyzed, mitigated, tracked (for mitigation progress), controlled (by design or operation), and communicated to project management. As the name implies, this is a continuous process.

Evidence of such an approach is found in the way NASA has been performing risk abatement in the Space Shuttle program. Shuttle has been using a form of continuous risk management on technical issues for the past two decades. Risks, as documented in Hazard Reports and in Failure Modes and Effects Analyses (FMEAs), are routinely reviewed every time a change in system configuration is proposed. If the change adversely impacts the control of an identified hazardous condition (risk) and cannot be resolved, then the proposal is withdrawn. The techniques for identifying risks are the hazard and FMEA process as described in NSTS 22254 and NSTS 22206, respectively. Any mission can easily incorporate the same approach with additional techniques to identify, analyze, and rank risks. These additional techniques are described in the Risk Identification and Mitigation Plan below.

The mission is ready for flight when every identified risk is properly managed with the acceptance of project and program management.

**Risk Identification and Mitigation Plan**

Continuous risk management, summarized above, is an efficient and suitable risk management approach for any mission. Continuous risk management provides a disciplined environment for proactive decision making to:

- assess continually what could go wrong (risks),
- determine which risks are important to deal with,
- implement strategies to deal with those risks,
- assure effectiveness of the implemented strategies.

The indications of risks in any complex mission follow the same fundamentals:

- Risk is usually present when there are relatively large energy transfers, where a slight deviation in configuration could result in an out-of-control situation.
- Risk also becomes very important when pushing existing technology to slim margins of performance capability.
- Risk is also present whenever numerous critical events with uncertain reliabilities must be performed to achieve mission success.
- There will continually be tradeoffs between mission performance and risk mitigation. Understanding the optimal influence of each will allow us to design a mission with the best chance of success in a reasonable amount of time.

The detailed approach for managing risks using continuous risk management is as follows:

Identify: Using existing information the team will identify mission risks for various mission architectures and system configurations. The risk identification contains at least one condition and at least one consequence in a clear and concise statement.

Analyze: Analyzing converts risk information into decision-making information by the process of examining the risks in detail to determine the extent of the risks, how they relate to each other, and which ones are the most important. The techniques in analyzing risks are detailed in Table 1.

**Table 1 - Risk Analysis Techniques and Mission Applications**

| Risk Analysis Techn | **Description** | **Example of Application** |
|---|---|---|
| Fault Tree Analysis (graphical) | A deductive (top-down) “Sherlock Holmes” analysis that begins with an undesired event and systematically attempts to find all possible causes. | Identifying system concept component undesirable events during the mission and their possible causes. |
| Event Tree Analysis (graphical) | A graphical analysis technique that explores system responses to operational “challenges”. May be used in time-related to assess event sequencing. | Evaluating the complexity of the mission; may be qualitative or quantitative. |
| Failure Modes and Effects Analysis (FMEA) (tabular) | An inductive (bottom-up) analysis technique that explores the way a system component can fail and | Identifying system concept component failure modes and their effects on the mission |

| | | |
|---|---|---|
| | the effects of that failure. | |
| Hazard Analysis (tabular) | An early system safety study of system hazards, and an assessment of their remaining risk after countermeasures have been proposed | Identifying potential hazards of the returned sample, and exposing the Earth environment to an uncontrolled release Martian soil. |
| Reliability Block Diagrams (graphical) | A graphical, logic mode generated analysis conducted in “success” space using modular construction with branch diagram representation. Illustrates system reliability during a defined time interval. | Identifying system concept component failure modes and their effects on the mission. A quantitative equivalent to FMEA |
| Probabilistic Risk Assessment | A quantitative approach to risk assessment. This involves the combination of event tree, fault tree, reliability block diagrams, qualitative analyses, and various supporting statistical analyses. | Assessing the overall risk, not from a predicted probability of success, but from a juxtaposed analysis and ranking of candidate mission architectures. |

Plan: Translating risk information into decisions and mitigating actions (both present and future), and implementing those actions or, the process of deciding what, if anything, should be done about a risk or set of related risks.

Track: Tracking a risk monitors risk indicators and mitigation actions in a process where risk status data are acquired, compiled, and reported and asks:

- Is the plan followed?
- Is the risk reduced?

Control: Controlling risks makes informed, timely, and effective decisions regarding risks and their mitigation plans. The process that takes the tracking status reports for the project risks and decides what to do with the risks based on the reported data.

Communicate and Documenting: Providing information and feedback to the project on the risk activities, current risks, and emerging risks.

Risks

Risk is simply the probability of occurrence of an undesirable event or condition and the consequence of that event or condition. Probability may be derived from a judgmental process or quantitative assessments. Typically for new programs there are little or no data for system or component failure rates. Also, the way systems interface with other systems is not known until some form of integrated testing is conducted.

Initial List of Risks

It is never too early to begin identifying risks. Risks may be identified by simple inspection or review of the mission overview, and as the concepts and formulation of the mission become better defined, identifying new risks becomes easier. In this process (CRM) one risk identified usually leads to another. Also, using a graphical risk assessment technique (see Table 1) can identify single point failures and risk drivers within a system or mission operations concept.

As risks are identified, before they become problems, the following approaches to assessing risk are in order of preference.

- Design for minimum risk. Risks should be eliminated by design wherever possible.

- Known risks that cannot be eliminated by design should be reduced to an acceptable level by the use of safety devices as part of the system. This includes redundancy.
- Where it is not possible to preclude the existence or occurrence of a known risk, provisions shall be employed for the timely detection of the condition and the generation of an adequate alert.
- Where it is not possible to reduce the magnitude of an existing or potential risk by design, or the use of alert provisions, special procedures shall be developed to counter the hazardous condition.

Risks may be identified to whatever level of resolution the design stage allows. Even though the design details are limited in conceptual and formulation stages, the comparison of risks between mission architecture is not ruled out by any means.

<u>References</u>


- Bioastronautics Critical Path Roadmap, baselined document, April 2001 (content available at http://criticalpath.jsc.nasa.gov)

- JSC 28354, NASA Human Rating Requirements, June 1998

- NPG 7120.5A, Continuous Risk Management


## 3.0 Risk Management Schemes (RKF)

No human endeavor is ever perfectly risk free, but numerous proven means exist to mitigate and minimize hazards. The following tactics will be employed

Protect The Public – The terrestrial public shall be protected against harm from departure and return disasters (debris, fire, contamination) through fault tolerance, range safety devices and safe location of facilities

Precursor Information – Advance knowledge of environmental conditions, engineered product performance and human response is invaluable to risk reduction. Minimizing unknowns via a prudent balance of ground demonstrations, in-situ robotic sampling and realistic in-space rehearsals is critical to mission success and safety.

Automated Asset Deployment – To meet the basic goals of safe scientific exploration and commercialization, the amount of time and risk permitted for the logistics of initial life support setup and maintainence should be minimized. Basic life support should be deployed by automated means and verified operational or repairable prior to utilization commitment.

Design Out Risk – To minimize reliance upon error prone and time dependent operational controls, the primary means of hardware and software risk mitigation requires solutions via design accommodations (e.g. fail safe redundancy, material selection, load margins, automation, inherent reliability, test verification, etc). Normal design criteria requires two fault tolerance for crew safety critical functions.

Maintenance Design – Maintenance is allowable as a complementary means to restore fault tolerance, non-critical functions and crew/vehicle safety. Because resupply at remote destinations is limited by transport time and constrained mass/volume, maintenance provisions must be available on site. Advance deployment of spares, component commonaility, in-situ manufacture, low level repairs, autonomous training/procedures, robotic implementation and preventative attention will be applied as tactics to ensure efficient and safe maintenance. Unless external isolation is impractical, all equipment susceptible to maintenance activities will be located internally. Whenever possible, all items that must nominally remain outside shall be capable of return to the cabin interior for repair. In general, crew time and logistics demands must be minimized and conducted under the safest possible conditions.

Hazard Isolation – Because life threatening failures inevitably occur, backup provisions are commonly implemented in advance. Remote placement of hazardous materials, redundant containment and cleanup means are just a few of the options. Hazardous devices and work zones shall be avoided or secured prior to approach by the crew.

Safe Havens - Using known technologies, a crewmember must be protected from environmental hazards such as low pressure, extreme temperatures, natural/artificial radiation and prolonged microgravity. The challenge of an exploration mission is to manage these risks safely without overly impeding mobility and work productivity. Traditionally, a micro and macro protection scheme has been applied successfully. If it is assumed that each individual works externally for 4 eight hour periods in a typical 168 hour week, less than 10% of that individual's total time would be spent externally. One third of overall time is spent asleep. When extreme conditions exceed suit or habitat protection capabilities, a use of the added safety of more robust shelter is called for (e.g. rover, portable enclosure or hardened zone of habitat). The overall crew protection approach combines the best of practical shielding technologies with limited exposure times, avoidance of exceptional conditions, supplementary shelters and advance warning.

Crew Support – Assistance supplied by earth or IVA based monitoring, control and advice is recommended to aid troubleshooting and during critical or high activity events. It is also beneficial for top level planning.

Return Assurance – When all else fails, the crew must have the option of prompt access to safe haven conditions. Self reliance, operational constraints and emergency provisions are essential. Simply remaining inside a sheltered vehicle or habitat for the majority of time decreases risk. While conducting work outside the vehicle, reduced margins for error dictate usage of the buddy system and constraints upon return assurance within life support and strength/endurance capabilities (e.g. time, distance and visibility). Unobstructed dual escape routes, rapid return vehicles and emergency life support are desirable implementation considerations. Active crew piloting for return safety during ascent and entry is **TBD.**

## 4.0 Time Allocations (RKF)

Crew time is typically over proscribed and micromanaged. The desire to maximize productivity and success drive this tendency. However, future long duration remote missions must escape this trend. By imposing and verifying limits upon each function and component that requires crew time, the primary mission goals can be accomplished with minimal impedence from overhead factors. Support from automation and robotics is absolutely essential for relief from mundane tasks. Daily and weekly allocations should be assumed as follows:

| DAILY | WEEKLY |
|---|---|
| Sleep = 8 hours<br>Pre and post sleep = 3 hours (incl hygiene and personal time)<br>Eating = 2-3 hours (EVA dependent)<br>Exercise = 0-2 hours (gravity and work dependent)<br>Task Planning/Reporting = 1.5 hours<br>Work = 6.5 hrs (IVA)<br>Work = 8.5 hrs (EVA, incl 2 hrs prep/post and airlock ops for 6.5 hrs external time) | 5 days of work<br>1 day of complete rest<br>1/2 day of maintenance and inventory mgmt<br>1/2 day of optional rest or light work & exercise<br><br><u>OTHER</u><br>Standard holidays<br>Monthly facility upkeep and refresher training days<br>Monthly medical examination (2 hrs each)<br>Dedicated crew handovers and resupply unloading |

| | |
|---|---|
| | 1 hour per maintenance task (incl setup/cleanup) |

To minimize vehicle design impacts and promote healthy crew interaction, small crews will use use single shift operations. Larger crews may use dual shift operations, but this will require additional provisions for physical separation and noise isolation to adequately assure simultaneous crew rest and work activities

When planning EVA operations, additional time constraints are applicable. Gravity transition adaptation time is dependent upon duration of initial gravity conditions. Allow 72 hours after prolonged 1G or partial G exposure prior to 0G EVA. Allow between 10 and 30 days between weeks/months at 0G and partial G EVA. Allow up to 1 day before partial G EVA after 7-10 days of 0G exposure. Assume a maximum of 4 active external work days per week. To assure sustained efforts, each crewmember must receive a day of light duties inside the cabin between each EVA excursion (no back to back days nominally). Each excursion will be limited to fit within the normal work day (7-8 hours including ingress/egress ops).
***DESIGN should allow for further use of EVA than planned to cover for contingency (DC)***
Depending upon the level of advance detailed choreography, a 20-50% time margin for unknown problems, inefficiencies and real time learning should be allocated.

## 5.0 Training/Procedures (RKF)

Crew and ground team training is essential for vehicle, payload, science, medical and logistics systems. Pre-flight training priorities will be focused upon crew safety. For short missions, mission success training and detailed choreography is essential. Long term flights rely heavily upon basic skills, in-situ, just-in-time and proficiency training. In all cases, clear, concise and validated procedures are necessary. Except for a limited number of emergency procedures, all actions should rely upon electronic media. To minimize cargo demands, training provisions should rely upon electronic presentation and nominally accessible hardware. Unique mass, volume and power resources for these functions must be minimized through commonality to approach zero.

Ground based facilities and personnel are a major influence upon human mission costs. To adequately simulate tasks in advance, it often requires multiple part task facilities to reproduce all the environmental variables. Any mission architecture must consider and minimize these infrastructure items. Savings can be leveraged by gracefully evolving development test equipment and software into crew training provisions. Consolidation and co-location of training facilities, personnel and equipment is another means of achieving cost efficiency. Designing for low maintenance, long life, hands off hardware turnaround, simple upgradability and off-the-shelf components is also extremely important. Facilities of interest include :

Computer simulations and system/environment models
Mockups of habitat, airlock, rovers (interiors and exteriors)
Planetary Surface Simulator
Weight Relief System (partial G and zero G)
Vacuum Chambers (unmanned, manned, environmental, dust rated, glove boxes)
Neutral buoyancy lab
Self Taught Training Media (for ground and crew)
Scale Models
Body and hand scanners
Exercise Devices

## 6.0 ANTHROPOMETRY AND BIOMECHANICS (Rajulu)

**Current Astronaut Height Selection Criteria**

Pilots: 64” (162.5 cm) to 76” (193.0 cm)
Mission Specialists: 58.5” (148.6 cm) to 76” (193.0 cm).

Reference: http://spaceflight.nasa.gov/shuttle/reference/factsheets/asseltrn.html

**Current Anthropometric Design Considerations**

Design and sizing of space modules should ensure accommodation, compatibility, operability, and maintainability by the user population. To fit 90% of the general population, the recommendation is to include a range of the users from the 5th percentile to the 95th percentile values for critical body dimensions. ***There should be a different approach to lead to consistent dimensions to allow for interchangeability in suit parts, etc. An option would be to take a one sigma or less range of human dimensions and design for that group of people***

Examples of Critical Body Dimensions

| Dimensions | 5th percentile | 95th percentile | Range |
|---|---|---|---|
| Stature | 148.9 cm (58.6”) | 190.1 cm (74.8”) | 41.2 cm (16.2”) |
| Sitting height | 78.3 cm (30.8”) | 99.5 cm (39.2”) | 21.2 cm (8.4”) |
| Arm reach | 65.2 cm (25.7”) | 88.2 cm (34.7”) | 23.0 cm (9.1”) |
| Sitting leg reach | no data | no data | no data |
| Chest Circumference | 30.3 cm (11.9”) | 89.4 cm (35.2”) | 59.1 cm (23.3”) |

Reference: NASA-STD-3000 Man-Systems Integration Standards

Issues/Unknowns

1. Some of the current body dimensions in the requirements documents are not relevant and the rest of the useful dimensions are not well defined. Hence, a detailed list of *relevant* critical body dimensions will have to developed that addresses issues related to designing space modules, suits, hardware etc.

2. There is a cost associated with the need to accommodate 90 percent of the adult population. It can be seen from the table above, the variation within each dimension is as high as 23 inches. One way to meet this constraint is to spend resources on a) developing hardware to accommodate all (example: custom made suits), b) modify the operations so that they can accommodate all (example: eliminate EVA with man in a can suit, develop escape module that will accommodate all crew instead of individual escape suit, etc), and c) reduce the range of variation in user population by restricting to a small range of population (example: from 5th to 50th or 50th to 75th). Hence there is a need to perform cost/benefit analysis on these three and other possible options.

**User Population Definition**

The current requirements documents (NASA-STD-3000, SSP57000B, etc) provide data for the 5th percentile Japanese female and the 95th percentile American male projected to the year 2000. This does not necessarily define the 5th and 95th percentile of the user population. The data in these documents are meant only to provide information on the size ranges of people of the world. Development of a predicted user population size range requires a statistical combination of an estimated mix of these data. Also, as pointed out by the Anthropometric Initiative document prepared by the Flight Projects Division (1999), different organizations use different data bases and some times wrong techniques to measure the astronaut population.

Issues/Unknowns

1. Develop the definition of the user population range based on the anthropmetric data base gathered by the Anthropometry and Biomechanics Facility (ABF) with the combination of three-dimensionally scanned data from the CAESAR project. ***Find the most common range of dimensions statistically and stick to that & then design to fit that range***

2. Consolidate all anthropometric data bases so that a single well defined and maintained data base can represent the relevant astronaut population.

**Application of Anthropometric Data Design Considerations**

Equipment, whether it be a workstation or clothing and work conditions, whether it be reaching or working, must fit the user population. The user population will vary in size (as mentioned before), and the equipment design and workplace guidelines must account for the variation in sizes. There are 3 ways in which a design will fit the user:

a) Single Size Specification for All: A single size specification may accommodate all members of the population. This is called Design for the Extreme. A translation passage, for instance, by allowing the tallest and biggest person, will allow everyone to use the passage. Similarly, a workstation that has a switch located within the reach limit of the smallest person, will allow everyone to reach the switch.

b) Adjustment- When it is not possible to select a single size, then a variable adjustment provision in the hardware can accommodate most of the user population (example: the foot control lever position or the seat.

c) Custom build - hardware and clothing for individual user.

During each design phase, a cost/benefit analysis must be done to choose the appropriate option.

**Variability in Human Body Size Design Considerations**

Microgravity effects:

a) Height increases by about 3% due to spinal elongation. Because past studies have been incomplete and poorly documented, proper studies are needed to define spinal elongation for short and long term exposure to microgravity.
b) Body Posture – The relaxed body assumes a curved posture- not scientifically studied well
c) Change in circumference- associated with fluid shifts and losses which are not very well documented
d) Mass loss – Because of bone and fluid losses, there is a reduction of body mass by about 3-4%. The rate of change and time to reach steady state conditions are TBD.

Partial gravity effects: There are no comprehensive studies on how body dimensions change when one is exposed to partial gravity environment.

Long Duration Mission effects: Long term exposure to micro- and partial gravity is not very well understood.

Return to Earth Effects: Data needs to be compiled from US-MIR missions as well as Russian missions and our ISS missions to document the return to Earth effects (such as how long does it take to recover the body mass, mobility, and the time to recover from joint limitations etc.)

Decadal Growth: The size of the general population is not static. For example, trends indicate that U.S. males are growing by TBD inches in height each decade.

**Strength Design Considerations**

Aspects of human strength that should be understood and considered in designing the space environment are prescribed as follows: a) maximum strength- ability to generate muscular tension and to apply it to an external object, b) endurance – ability to perform tasks under submaximal condition –isometrically or isotonically, c) functional strength – ability to perform tasks such as gripping, grasping, turning a knob, hammering, pushing, pulling, carrying, building, etc. d) tool based strength exertions – screwdriver, hammer, wrench, ratchet, wheel, rack, etc.

Issues/Unknowns

The current design requirements in the NASA-STD-3000 as well as in the SSP57000B do not provide all the necessary data for designing a space hardware or tools. In order for 90 percent of the user population to perform these tasks either the tools should be designed based the ***minimum*** capability of the user population and at the same time designed to withstand the ***maximum*** capability of the use population. Unfortunately, the brute strength, functional strength, and tool specific strength data has been limited and not updated properly.

Much of the data in space program related documents are based on earth gravity environment. Efforts should be made to gather strength data in reduced gravity environments. Efforts should also be made to understand the human strength capabilities during long term missions since there is evidence to show that muscle atrophy takes place in reduced gravity environments.

Suit Effects: A recent study (Gonzalez et.al, 2001) and other earlier NRA studies by Maida have shown that wearing a suit reduces the strength capacity by about 40%. In addition current NIOSH guidelines recommend allowable capability to be at or about 30 percent of maximum capabilities. Hence, strength requirements for EVA related operation may be extrapolated from earth gravity studies. ***Should look at technologies and designs to increase strength***

**For additional detailed information, refer to Appendix A.**

## 7.0 Reduced and Variable Gravity Limits (Charles)

**TBD**

## 8.0 Acceleration, Vibration and Impact Limits (Charles)

**TBD**

The maximum deceleration load upon the crew after long duration microgravity exposure shall be 5G (RKF – Mars DRM book)

## 9.0 Noise Environment and Acoustic Load (Allen and Goodman)

There are several detrimental effects of a noisy environment on human beings. From the most severe to the least, these include:

- physical damage to the sensing organs of the ear resulting in permanent or temporary hearing loss;
- speech and communication interference resulting in potentially unsafe vehicle operating conditions
- psychological stress possibly resulting in hypertension, loss of sleep, fatigue, irritability, loss of productivity, distraction, possibility of making more errors in judgment or in physical activities, or loss of morale.

The most severe of these effects are associated with the loudest levels of noise; however, even moderate levels of noise over extended durations can cause auditory damage and hearing loss. Hearing loss effects individuals differently and can be temporary or permanent. These hearing losses are classified as temporary threshold shifts (TTS) or permanent threshold shifts (PTS), respectively.

As opposed to industrial workers, the crews of spacecraft do not have the opportunity to go home at night to escape their noisy work environment. Also, we don't expect punch presses, saws, or other equipment to be used in manned spacecraft as in factories/industry or as in other high noise work environments. For these reasons, space vehicles are required by NASA to meet more stringent noise requirements than the Occupational Safety and Health Administration (OSHA) levies on workplaces for an eight-hour day. In addition to the consideration of 24 hour per day exposure, NASA space flight requirements also vary depending on the nominal duration of the mission.

Failure to maintain reasonable levels in extended noise exposure situations has in the past led to many cases of hearing loss. For example, hundreds of US Navy personnel have experienced significant hearing loss during submarine and ship missions resulting in the US government having to spend millions of dollars annually to pay for hearing aids for veterans. In another example, a very high percentage of MIR cosmonauts experienced TTS, several of which were disqualified from further space flights because of their hearing loss. Hearing protection can provide some small amount of relief but are only comfortable to wear for a few hours and so are ineffective as a permanent solution, and so in many cases don't alleviate the 24 hour exposure concern.

Sources of noise on flight vehicles include fans, pumps, compressors, motors, air ducting, actuators, exercise equipment and rotating machinery among other items which are required to keep the atmosphere circulating and keep the crew healthy as well as cool the science experiments, computers and other equipment. On a given flight vehicle, there are hundreds of these items, and the cumulating noise emissions of these devices create the vehicle habitable volume's acoustic environment. Vibration isolation, sound containment, sound dampening and machinery balancing are some of the measures available for quieting these sources.

<u>Acoustic Metrics</u>

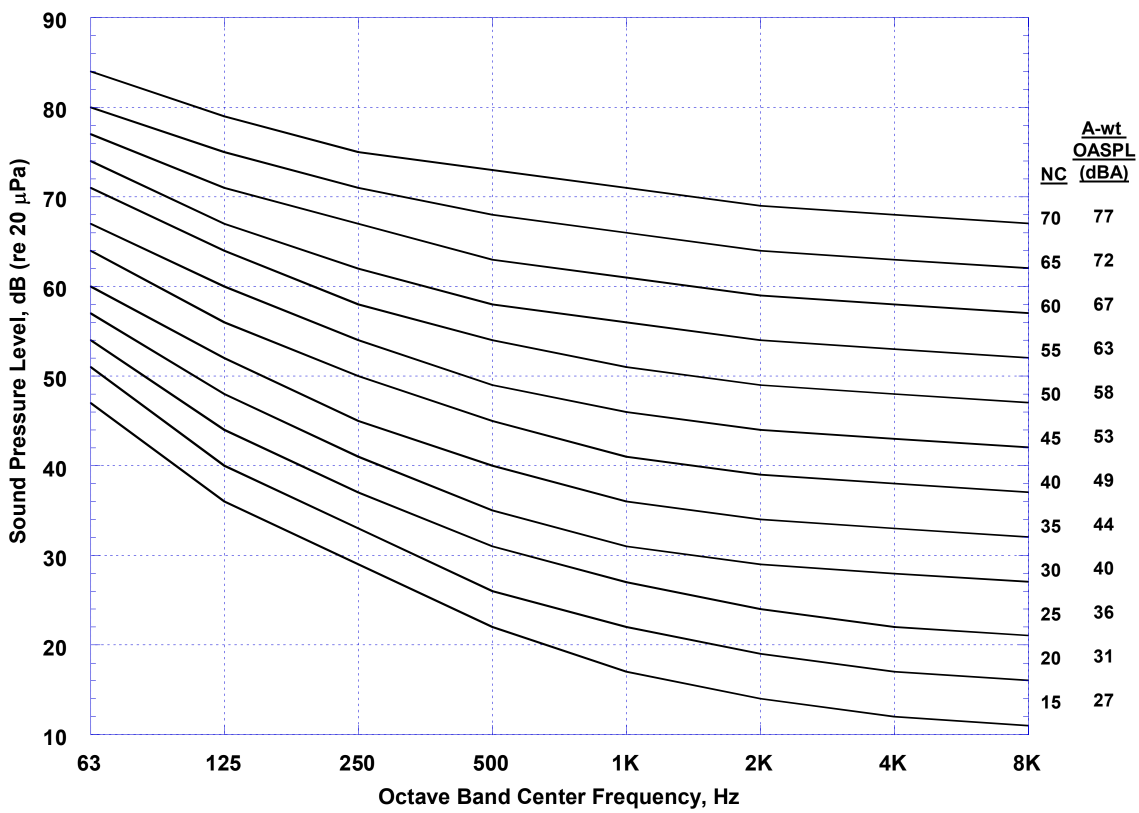
In order to understand noise requirements, it is first necessary to understand how sound is characterized. The most basic characterization of noise is in terms of magnitude (level), pitch (frequency) and duration of the sound. Because of the vast range in acoustic pressures detectable by the ear, a logarithmic description of the fluctuating sound pressure has been adopted to rate noise levels. This so-called sound pressure level (SPL) is described in decibels (dB) with a reference pressure fluctuation of 20 micropascals, the lowest acoustic level detectable by an average young adult male at a frequency of 1000 Hz.

Considering pitch, the human ear is sensitive to sounds between approximately 60 and 20,000 Hz, with the greatest sensitivity in the frequency range between 1000 and 5000 Hz. When considering spectral frequencies in octave bands, the ear at 60 Hz is approximately 25 dB (more than an order of magnitude) less sensitive than at 1000 Hz. Because of this dependency on frequency, weighting systems were devised to emphasize certain frequencies more or less so that the levels of the different frequency bands could be combined together to provide a single number to assess a spectrum of noise against the response of the human ear. The weighting system that is used most often for this purpose is the A-weighting system and the resultant of combining the spectral levels using this weighting system is denoted the A-weighted overall sound pressure level (A-wt OASPL) which is given in units of dBA re 20 Pa.

In terms of duration, there are noise producers that operate continuously and there are those that operate intermittently. In order to characterize a noise environment that is produced by differing numbers of continuous and intermittent sources, a time-weighted average of the A-wt OASPL is

taken over a period of time thus providing an equivalent SPL, $L_{Aeq}$. For a typical earth workday, the duration used is 8 hours, but for spacecraft environments, the applicable integration period is 24 hours. The corresponding equivalent SPLs are denoted $L_{Aeq8}$ and $L_{Aeq24}$, respectively.
While the equivalent SPL and A-wt OASPL provide effective, easy-to-use metrics for noise exposure and noise level quantification, respectively, these metrics are an oversimplification of the environment, since the frequency content is important to quantify and control. Attention to the frequency content is important because of: greater sensitivity to noise in specific frequencies; the speech interference levels fall within a limited range; and high spikes or levels in some frequencies can be very irritating or annoying and dominate overall broad band noise level concerns. Specifically, these criteria do not address the spectral shape of the acoustic environment. To satisfy the need for this more comprehensive and rigorous specification, NASA utilizes the Noise Criteria (NC) curves, which were developed to quantify room noise effects on speech communications. A partial set of the NC curves is shown in **Figure 1**.

**Figure 1. NC Curves**




### *Acoustic Specifications for Mission Durations of 4 Months*

For regulating workplaces, the National Institute of Occupational Safety and Health (NIOSH) has recommended that OSHA use an $L_{eq8}$ of 85 dBA as the recommended exposure limit with hearing protection required for personnel exposed to $L_{eq8}$ levels of 85 dBA or higher.

For the reasons stated above, NASA regulations are necessarily more stringent. For space shuttle flights, which are typically no more than 2 weeks in duration, the flight rules states that when $L_{Aeq24}$ levels of 74 dBA or above occur, specific actions will be taken including the wearing of hearing protection as well as actions to reduce the acoustic load on the crew. For the International Space

Station (ISS), the flight rules state that beginning at $L_{Aeq24}$ levels of 67 dBA hearing protection is required for an amount of time given by **Table 1**.

**Table 1. ISS Hearing Protection Requirements versus 24 hour noise exposure levels**

| $L_{Aeq24}$ | **65-66** | **67** | **68** | **69** | **70** | **71** | **72** | **73** | **74-75** | **76-77** | **>77** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hours per day of hearing protection required (in addition to 2 hour exercise period) | 0 | 2 | 7 | 11 | 14 | 16 | 17 | 19 | 20 | 21 | 22 (full time) |

The above exposure limits levied by NASA where hearing protection are required specifically address the concern of crew hearing loss. However, in order to address the concerns of speech communication effectiveness and psycoacoustic effects, NASA stipulates additional noise requirements. These requirements also serve as controls to insure that the noise environments in space vehicles do not approach the levels specified in the flight rules.

The additional requirements discussed here apply to the ISS, and are used as illustrations because they apply to relatively long duration missions, up to 4 months in length. However, longer duration missions should require even more stringent acoustic environment requirements.

In addition to the $L_{Aeq24}$ noise exposure limits, NASA ISS specifications include limits on the noise emitted into the crew's habitable volume by ISS modules, payloads, and government furnished equipment (GFE). These specifications are divided into continuous and intermittent emissions and are as follows:

<u>Continuous Noise Emission Limits</u>

1) Modules in the US segment shall not exceed NC-50 at the center of the module's habitable volume, including noise emitted by the integrated GFE. In addition, the sleeping environment shall not exceed NC-40 (SSP 41000). The Russian segment modules have roughly equivalent but different requirements which will not be discussed for clarity.

2) The compliment of payload racks in a given module shall not exceed NC-48 when evaluated at the center of the module's habitable volume (SSP 57011). To implement this specification, the NASA Payloads Office has specified that each payload rack shall meet the NC-40 criteria when measured 2 feet from the loudest point on the rack (SSP 57000). Furthermore, in order to meet this rack requirement, rack integrators specify a sub-allocation to the individual payloads that are typically close to NC-32.

3) Non-Integrated GFE shall not exceed the NC-40 criteria when measured 2 feet from its loudest point (JSC 28322).

<u>Intermittent Noise Emission Limits</u>

**Table 2** specifies the intermittent noise emission limits for ISS payloads and non-integrated GFE. The limits apply to measurements performed 2 feet from the loudest point on the item. Items that have operational durations longer than 8 hours must comply with the continuous noise limits stated above. Modules with their integrated GFE have no relaxed requirement for intermittent noise sources.

**Table 2. Intermittent Noise Emission Limits**

| Maximum Noise Duration per 24-hour Period | A-wt OASPL, dBA re 20 μPa |
|---|---|
| 8 hours | ≤ 49 |
| 7 hours | ≤ 50 |
| 6 hours | ≤ 51 |
| 5 hours | ≤ 52 |
| 4 hours | ≤ 54 |
| 3 hours | ≤ 57 |
| 2 hours | ≤ 60 |
| 1 hours | ≤ 65 |
| 30 minutes | ≤ 69 |
| 15 minutes | ≤ 72 |
| 5 minutes | ≤ 76 |
| 2 minutes | ≤ 78 |
| 1 minute | ≤ 79 |
| Not Allowed | ≥ 80 |

Additional Recommendations

In addition to the requirements discussed above, the ISS Flight Crew Integration Standard, SSP 50005, recommends additional limits on the acoustic environment of the crew's habitable volume including:

1) Impulsive noise, i.e. noise with duration less than one second, shall not exceed 140 dB.

2) Infrasonic noise shall be less than 120 dB in the frequency range from 1 to 16 Hz for a 24-hour exposure.

3) The reverberation time in areas where crewmembers must communicate by voice shall be between 0.4 and 0.6 seconds for sound in the 1000 Hz Octave Band.

Acoustic Risk Mitigation and Countermeasures

Ground based testing, empirical predictions, and on-orbit measurements are all used in conjunction with remedial actions and countermeasures to insure a safe acoustic environment on the ISS. First, ground based testing is performed on all noise producing hardware in order to insure compliance with the specifications. Coupled with this testing activity are prediction activities, which combine the test data along with assumptions about equipment installation effects and reverberation effects to predict the acoustic environment on the ISS at any stage of the mission.

Finally, on-orbit measurements are made on the ISS to verify that the acoustic environment is appropriate. These on-orbit measurements employ sound level meters to measure acoustic spectra and A-wt OASPLs at specific locations. The measurements also use acoustic dosimeters to measure the $L_{Aeq24}$ noise exposure levels. And as a final safety check, on-orbit audiometry is performed to monitor the hearing sensitivity of the crew.

Noise emission problems are fixed on the ground if possible, but if a problem remains on-orbit, it is reviewed and can be fixed on-orbit with remedial actions such as vibration isolators, and sound absorbing or blocking materials. As a last resort, acoustic countermeasures are employed. These countermeasures include hearing protection including passive bulk and molded earplugs as well as active noise control headsets. ***Noise canceling technology?***

Considerations for Long Duration Spaceflight

For mission durations in excess of a year, it will be important to achieve a low level of ambient noise in the vehicle environment, on the order of NC-43. These levels are achievable but to do this, concern for acoustics must be included in the vehicle's design phase. Simple design features such as well-placed absorbent panels, equipment isolators and sound absorbers can be quite effective and simple to incorporate in the design, but expensive or impossible to employ as a band-aid fix to the actual vehicle. And the fact that the vehicle might not be accessible, if out of Earth orbit, makes it imperative that the vehicle components not require remedial actions.

From an acoustic load perspective, it is also recommended that a quiet place be provided for the crew to recover from the higher acoustic levels of the working space without having to use hearing protection. On the ISS, the crew quarters are required to be quieter than the rest of the vehicle; however, these quarters are just large enough for a crewmember to sleep in. It would be desirable to design a portion of the long-range vehicle, in addition to the sleeping quarters, to be especially quiet where the crew can relax and unwind. To help with this, the emerging field of active noise control could be employed to eliminate the low frequency noise, while more traditional methods are used to handle the high frequency noise.

*Acoustic Information Sources*

- SSP 41000, System Specification for the International Space Station
- SSP 57000, Pressurized Payloads Interface Requirements Document
- SSP 57011, Payload Verification Program Plan
- JSC 28322, ISS Acoustic Requirements and Testing Document for ISS Non-Integrated Equipment
- SSP 50005, International Space Station Flight Crew Integration Standard
- Human Spaceflight, Mission Analysis and Design, Larcon, M. and Pranke, L., McGraw-Hill, 2001.
- Noise and Vibration Control Engineering, Baranek, L. L.. and Ver, I. L., John Wiley & Sons, Inc., 1992.
- Handbook of Acoustics, Crocker, M. J., John Wiley & Sons, Inc., 1998.
- Engineering Noise Control, Theory and Practice, Bies, D. A. and Hansen, C. H., E&FN Spon, 1988.
- Criteria for a Recommended Statdard, Occupational Noise Exposure, Revised Criteria 1998, DHHS (NIOSH) Publication No. 98-126

Noise (M. Rudisill Input)
May be serious concern on long duration mission. Poor noise control has biomedical and performance issues. Real issue because internal atmosphere must always be blown around, causing constant "background noise." Also causes problem in communications (must wear headset all the time) and how noise interacts with internal atmosphere and pressure. Noise tolerance has individual differences. Must establish spacecraft noise sources, must allow crew control of noise.

## 10.0 Sensory Adaptation (Charles and Rudisill)

**TBD**

## 11.0 Metabolic Rates (rest, normal, max) - Tri

The metabolic rate of a human being is defined by the rate of heat produced by the body within a given time. This rate is expressed in units of kcal/hr (BTU/hr). The metabolic rate typically is divided into three basic levels: resting rate, normal (mean) rate, and maximum rate. Additionally, typical metabolic rates can be designated by crew environment: microgravity vehicle habitat, lunar gravity surface habitat, martian gravity surface habitat, microgravity space suit, lunar gravity space suit, and martian gravity space suit. Please refer to the following table for specific metabolic rates:

| Crew Metabolic Environment | Resting Rate (kcal/hr) | Normal Rate (kcal/hr) | Maximum Rate (kcal/hr) |
|---|---|---|---|
| Microgravity vehicle habitat | | | |
| Lunar gravity surface habitat | | | |
| Mars gravity surface habitat | | | |
| Microgravity space suit | 65 | 250 | 400 |
| Lunar gravity space suit | | | |
| Mars gravity space suit | | | |

References = Man-System Integration Standards, NASA-STD-3000, Section 14.2.3.5

## 12.0 Cabin Pressure (Kosmo)

Beyond assuring long term crew safety and health, the internal atmospheric pressure level and composition in habitable elements of future long term space and planetary surface missions must be optimized for efficient equipment operations and crewmember productivity. Selection of the atmospheric pressure level and composition has critical effects on technology and engineering requirements of the EVA systems and moderate effects on engineering requirements of the life support and thermal control systems for future mission considerations. Ideally, a synthesize range of suitable internal atmospheric pressure levels and compositions should be considered in order that an optimal combination can be selected to satisfy all significant and major mission requirements as well as primary mission goals and objectives.

A main function of the atmospheric pressure control and composition of the life support control subsystem is to maintain the oxygen partial pressure between the hypoxia low and oxygen toxicity or flammability high limits. The following chart shows the various normoxic pressures and concentrations which are equivalent to that at sea-level.

| TOTAL PRESSURE PSIA | NORMOXIC PARTIAL PRESSURE PSIA | NORMOXIC CONCENTRATIONS % |
|---|---|---|
| 3.7 | 3.70 | 100 |
| 4.0 | 3.62 | 90.5 |
| 5.0 | 3.45 | 69.0 |
| 6.0 | 3.36 | 56.0 |
| 7.0 | 3.29 | 47.0 |
| 8.0 | 3.24 | 40.0 |
| 9.0 | 3.20 | 35.5 |
| 10.0 | 3.17 | 31.7 |
| 14.7 | 3.08 | 21.0 |

Although the natural design inclination would be to set oxygen partial pressure at a control level such as to reduce time for physiological acclimatization, it may be possible with the extended times of expected future long term missions to actual set the oxygen partial pressure at the lower tolerance limits. Many people live and function at less than normoxic sea-level conditions; and, likewise, many physiological changes associated with spaceflight represent normal adaptations in order to establish a homeostasis appropriate to the new environment. The lower oxygen partial pressure situation would also reduce overall flammability concerns. The above chart also shows that the normoxic concentration increases with decreasing total pressure. Since the flammability of materials increases with oxygen concentration, it would be preferable from the habitat materials standpoint to have a higher total habitat pressure. Assuming that habitat materials will be selected based on flammability testing ***based on appropriate oxygen concentration levels***, a total habitat atmospheric pressure of 68.9 kPa (10.0 psia) would be acceptable from both a materials aspect as well as being physiologically acceptable. ***Skylab experience also demonstrated that crewmembers and selected materials could function well at the 34.5 kPa (5.0 psia) pressure level.***

In regard to EVA operations, the EVA system prefers a low suit pressure to maximize crewmember mobility, especially glove dexterity, and to reduce overall suit structural weight. From an operational standpoint, in order to reduce or eliminate mission timeline overhead and support equipment requirements for prebreathe activities prior to conducting EVA operations, it would also be desirable to maintain a lower cabin pressure environment. Based on Shuttle EVA operational experience, it has been demonstrated that routine EVA operations can be conducted from a 70.3 kPa (10.2 psia) cabin with a 29.6 kPa (4.3 psia) space suit after a minimum prebreathe period (40 minutes) and represents an acceptable bends risk ratio (R) of approximately 1.65. ***Also, Skylab EVA operations were conducted from the 34.5 kPa (5.0 psia) cabin environment (70% oxygen/30% nitrogen) with a 26.2 kPa (3.75 psia) space suit without a prebreathe operation which represented a very low acceptable bends risk ratio (R) of 0.4.***

Based on the abovementioned factors regarding human physiology concerns ***as well as to minimize materials oxygen compatibility and flammability issues, and in support of conducting routine EVA operations without prebreathe overhead impacts; a cabin pressure level regime of 34.5 kPa (5.0 psia) with a 70% oxygen/30% nitrogen concentration level and supported by a 26.2 kPa (3.75 psia)*** space suit system would be an acceptable choice for future long term space missions.

**For additional background information and references, refer to Appendix B.**

## 13.0 CO2, trace gas and humidity limits (Tri)

Carbon dioxide (CO2) partial pressure maximum limits for space habitat atmospheres are as follows:

- 400 N/m2 (3.0 mmHg) max for normal operations
- 1013 N/m2 (7.6 mmHg) max 90-day for degraded operations
- 1600 N/m2 (12.0 mmHg) max 28-day for emergency operations

Dewpoint (humidity) maximum levels for space habitat atmospheres are as follows:

- 278 – 289 K (40 – 60 deg F) max for normal operations
- 274 – 294 K (35– 70 deg F) max 90-day for degraded operations
- 274 – 294 K (35 – 70 deg F) max 28-day for emergency operations

There is a wide assortment of trace gases that can be found in space habitat atmospheres, each having an established Spacecraft Maximum Allowable Concentration (SMAC), typically in concentrations of parts per million (ppm) or parts per billion (ppb).

References = Man-System Integration Standards, NASA-STD-3000, Section 5.1.3.1

## 14.0 Material Selection (RKF)

Basic material selection and properties must not induce hazards to the crew. Test validated materials must be chosen which do not exceed allowable limits for toxic offgasing/outgassing or flammability. This constraint applies to both metallics and non-metallics. Potentially hazardous materials that cannot be avoided should be reliably contained or isolated. The flammability triangle of fuel, oxygen and ignition source must be broken. Atmospheric pressure and composition have large influence upon material safety. For example, exceeding 4% hydrogen concentration or 30% $O_2$ concentration leads increases ignition chances and decreases material selection options (in the case of $O_2$). Biologically hazardous fluids, chemicals, particulates and microbes should also be contained, isolated or eliminated.

## 15.0 Radiation (Rudisill)

### Introduction

Among the physical agents potentially resulting in adverse health risks are the naturally ocurring and the technology produced radiations and fields. Natural radiations can be a health hazard and shielding from this hazard is a normal part of the design process. The natural magnetic fields are of no direct hazard and provide added protection from some natural radiations in some regions of space but also add radiation fields in magnetic trapping regions. Technologically produced radiations result from nuclear power sources, diagnostic devices, self-illuminating instruments, and microwave devices. Device generated magnetic fields can be a health hazard especially intense superconductor generated magnetic fields.

Ionizing radiation is a major health hazard everywhere in space and on many planetary and satellite surfaces. Galactic cosmic rays (GCR) permeate the galaxy and consist of all ions of the natural chemical elements moving with speeds approaching the speed of light (including ions of high-charge and -energy, HZE). The GCR diffusion into the solar system is balanced by the outward convection current resulting from the expanding solar coronal plasma. The result is a net decrease of the GCR intensity with decreasing heliocentric radius. Solar particle events (SPE) are produced by dynamic solar events and mainly in the transition region between a large coronal mass ejection (CME) and the normal interplanetary medium. The SPE composition is mainly ions of the chemical elements through iron but is dominated by hydrogen and helium ions to energies of several hundred or so MeV. The lower energy GCR and SPE ions are eliminated within the trapping regions of a planetary magnetic field but have free access in Polar Regions. Albedo neutrons are produced in planetary atmospheres and surfaces and can be a significant source of human exposures. The albedo neutron decay produces electrons and protons which can have long lifetimes in the magnetic trapping regions giving rise to intense trapped radiation belts. Nuclear power sources generate mainly neutrons and gamma rays and require careful shielding and operational consideration.

Ionizing radiation injury is ultimately related to cellular events from the physical insult although the cell matrix also plays a role. The first line of defense against physical insult is the cell wall, but provides no effective barrier to ionizing radiation. The main action of the ionizing radiation is to break chemical bonds and form free radicals resulting in direct and indirect injury to the cell genome. The injury results in a cell response moderated by the cell matrix, which may be injurious to the individual. Two categories of biological injury are regulated: *deterministic effects* for which the severity of the effect is related to the level of exposure (e.g., nausea) and *stochastic effects* for which the risk (or probability) of the effect is related to level of exposure (e.g., cancer).

Radiation Quantities. Radiation exposure is quantified as the energy absorbed by a unit mass of tissue (D, dose). The unit of dose is Gray (Gy) representing 1 J/kg and is related to the older unit rad as 1 Gy = 100 rad. This dose correlates well with biological risk for radiations which uniformly deposit energy throughout the cell structure or so-called low-LET (linear energy transfer) radiation such as x-rays, gamma-rays, electrons, and muons. In this case a high dose is associated with the random hits of many particles leading to a uniform exposure. Basic data on biological injury in humans is mainly from such low-LET radiation from the detonations of nuclear weapons during World War II and accidental exposures. Cell, plant, and animal studies with high-LET radiation (mainly neutron and alpha decay particles which may not be related to the HZE particles in space) result in a greater number of effects at the same dose of low-LET radiation. The ratio of doses resulting in the same biological effect from low-LET radiation and from high-LET radiation is called the relative biological effectiveness (RBE). The quantity which relates dose to biological effect for a given radiation type is called Gray-equivalent (Gy-Eq) and is given by $\text{Gy-Eq} = \text{RBE} \times D$. Hence, Gy-Eq is the numerical amount of gamma-ray dose resulting in the same effect as the dose D of any arbitrary radiation exposure. Large RBE values have been observed for neutrons (RBE values of 500 for hair mutations in tradescantia and of 100 for neoplastic transformations in mouse embryo cell cultures) and for low-energy alpha particles (RBE of 250 in developing hemopoiesis in mouse embryo). Effectively infinite RBE's have been observed for sister chromatid exchanges (HZE ions) and genomic instability (alpha particles). This relative biological effectiveness has been used in a regulatory sense by defining the dose equivalent $H = Q(\text{LET}) \times D$ where Q(LET) is a defined function of LET for regulatory purposes and judged on the basis of RBE studies and their relation to hurt of the individual. The unit of H is Sievert (Sv) and is numerically equal to D for low-LET radiation where Q (and RBE) is unity.

Regulation of Space Radiation Exposure. Regulatory requirements have been established for operations in LEO to control stochastic and deterministic radiation effects. The *stochastic effect* limit is based on the lifetime excess fatal cancer risk (not more than three percent). This limit is based on Effective Dose including a sum over weighted dose equivalent to specific tissues. Currently accepted sex and age dependent cancer risks limits are in terms of dose equivalent (NCRP 98). On the basis of more recent cancer risk evaluations the recommended limits have been greatly reduced (NCRP 132). *Deterministic effect* limits are for thirty day, annual, and lifetime periods for three critical tissues: ocular lens, skin, and blood forming organ (BFO). Currently accepted limits are in terms of dose equivalent with the stochastic Q used as a proxy for the appropriate RBE (NCRP 98).

Since the recommendations of current limits, it has been established that solid tumor deaths are five times more likely than assumed in the older limits and RBE values for deterministic effects have been established. New regulatory requirements for LEO operations have been recommended (NCRP 132) as given in tables 1 and 2. In addition to exposure limitations, US regulatory requirements are to keep exposures As Low As Reasonably Achievable (ALARA). The space program must go beyond the simple limitations of tables 1 and 2 and demonstrate ALARA has been achieved in the designs used and operations made in space.

Unlike LEO exposures which are often dominated by trapped radiation, deep space exposures are dominated by GCR for which there is insufficient data on biological effects and there are no specific exposure requirements for deep space operations. Still large contributions to ISS exposures are from GCR leading to large uncertainties in the ISS shield design. For mission studies, the quantities and limits defined for LEO operations are usually used.

**Table 1 Recommended organ dose limits for deterministic effects (all ages) for LEO operations (NCRP 132, 2001)**

| | Bone Marrow (Gy-Eq) | Eye (Gy-Eq) | Skin (Gy-Eq) |
|---|---|---|---|
| Career | - | 4.0 | 6.0 |
| 1 y | 0.50 | 2.0 | 3.0 |
| 30 d | 0.25 | 1.0 | 1.5 |

**Table 2 Ten-year career E limits based on three percent excess lifetime risk of fatal cancer in LEO operations (NCRP132, 2001)**

| Age at Exposure (y) | E (Sv) | |
|---|---|---|
| | Female | Male |
| 25 | 0.4 | 0.7 |
| 35 | 0.6 | 1.0 |
| 45 | 0.9 | 1.5 |
| 55 | 1.7 | 3.0 |

[a]Limits are expressed in effective dose *E*.

Uncertainties in Exposure Risks Estimates

Uncertainties in space radiation health risk estimates have several sources. The greatest source is in human health risk data coming from the two detonations of nuclear weapons during World War II. These exposures were low-LET high-dose-rate exposures of a fixed population of individuals with no direct dosimetry from which comes the estimates of high-dose-rate risk coefficients in various age groups. Uncertainty arrises in these high-dose-rate risk coefficients from the uncertainty in dosimetry, in statistics from the limited number of survivors, in projection of the fatal cancer risks over the lifetime remaining (cause in recent changes in risk estimates), and in relationship of these risk coefficients for this population to other national/ethnic groups. Further uncertainty enters in application of the high-dose-rate risk coefficients to low-dose-rate exposures, the RBE for other radiation types, and the estimation of dose to specific tissues from space radiations for a specific mission.

Detailed analysis (JSC 29295) has shown that the main limitation to shield design in deep space results from uncertainty in applying the known risk coefficinets with their associated uncertainty to the space exposures and not the related evaluation of the exposure conditions. The greatest uncertainty arrises from the uncertainty in the RBE of different radiation types (or quality factor) while the remaining uncertainty in risk coefficients from other sources is comparable to uncertainty arrising from estimation of LET related dose contributions in specific tissues for the specific space shielding.

III. Radiation Countermeasures & Risk Mitigation

No single method is relied on for the protection of astronauts from the effects of space radiation. The first step is to control the radiations reaching specific tissues through shielding and choice of exposure conditions. The second is to control exposure based on individual sensitivity (currently age and sex). Finally, the control of effects through medical intervention. These methods are implemented through mission planning, shield design, operational methods, and biological treatment and controls.

*Design, Technology, & Shielding*. Exposures can be reduced for specific missions through planning, technology choices, and shielding. Solar cycle variation can reduce GCR exposure by limiting launch windows with a rising risk of SPE exposure which is resolved using a “storm shelter” approach. Advanced propulsion systems can reduce the transit times where exposure rates are most intense. Shielding against the radiation environment envolves the totality of the spacecraft and design choices can have adverse effects on radiation exposures (e.g. aluminum structures as opposed to polymer composite structures). Note that the design process will be a collaboration among all the disciplines to arive at an optimum arrangement and multidisciplinary optimization (MDO) methods with multifunctional materials database will be required. Shielding of every aspect of the mission is necessary to assure astronaut safety. For example, spacesuits and rovers are least protected due to mobility requirements and close attention needs to be given to assure safety during the period of a SPE while cover is being found. There is a corresponding relation to operational methods and possible medical considerations in mission planning.

*Operational Methods*. Operational considerations usually address two issues. First, the scheduling of activity is avoid to the extent possible regions and times when exposure levels are known to be high. The duration of time spent by the astronaut in such places or during such times when exposure rates are elevated. Second, some environmental components are dynamic and can undergo unexpected fluctuations so that monitoring the environment and making short term predictions will guide emergency conditions to limit exposure. In both cases, personnel monitoring for record keeping and career and possible medical treatment planning is a necessary part of operational methods.

*Biological Countermeasures.* The understanding of the molecular basis of radiation action is expected to lead to biological counter measures for risk mitigation. An effective countermeasure must work for extended periods, be effective for high-LET radiations, and lead to minimal side effects. It could be a combination of radioprotectants, diets of anti-oxidants, and enzymatic modifiers can greatly reduce the health risks. – JSC 29295

***Address selection criteria, such as age, sex, and genetic tolerance to radiation***

A detailed analysis of the potential improvements in space operational capability from these factors has been made and the results in terms of expected number of days gained in space is given in table 3. Additional details are given in report “Space Radiation Cancer Risk Projections for Exploration Missions: Uncertainty Reduction and Mitigation,” by Cucinotta et al. listed among the Radiation Information Sources at the end of this section.

**Table 3. Estimates of increased number of safe days in space from different mitigation or other areas (JSC 29295).**

| *Approach* | *Expected No. of Days Gained* | *Comment* |
|---|---|---|
| Improved Risk Assessment | 200-400 days | Cost effective approach using data collection and research |
| Shielding | 50-300 days | Light mass materials identified, risk assessment data needed to improve approach |
| Advance Propulsion | 100-300 days | Large advantage if achievable |
| Crew Selection | 50-300 days | Age, sex, genetic selection not ethical. Role of sensitivity to GCR not |

| | | |
|---|---|---|
| | | established at this time |
| Biological<br>Countermeasures | 0-1000 days | Needs revolutionary research to achieve |
| Solar Cycle Effect | 100-200 days | Reduces launch windows and increase SPE threats |

IV. Research & Technology Requirements

**TBD**

V. Radiation Information Sources

- Space Radiation Health Project http://srhp.jsc.nasa.gov/
- NCRP Report No. 132: Radiation Protection Guidance for Activities in Low-Earth Orbit
- JSC-29295: Space Radiation Cancer Risk Projections for Exploration Missions: Uncertainty Reduction and Mitigation
- Nicogossian & Parker. Space Physiology & Medicine. NASA SP-447. (1982). Later version?
- Wilson, Miller, Konradi, and Cucinotta. Shielding Strategies for Human Space Exploration. NASA Conference Publication 3360 (December 1997).
- Critical Path Roadmap (CPR)
- Space Radiation Health Project, NASA JSC (2000)
- Strategic Program Plan for Space Radiation Health Research, NASA Publication (1998)
- Space Radiation Health Project, Biomedical Research and Countermeasures Program Implementation Plan, NASA JSC (1998)
- Review of NASA's Biomedical Research Program, National Academy of Sciences Publication (2000)
- International Standard Book No. 0-309-06885-1, Radiation and the International Space Station: Recommendations to Reduce Risk; Space Studies Board, NRC, NAS (2000)
- NASA/LBNL #40278: Modeling Human Risk: Cell & Molecular Biology in Context
- Radiation Hazards to Crews of Interplanetary Missions, NAS, (1996)
- Radiation Guidance on Radiation Received in Space Activities, NCRP Report No. 98 (1989)
- HZE – Particle Effects in Manned Space Flight, NAS, (1973)
- Radiation Protection Guides and Constraints for Space-Mission and Vehicle-Design Studies Involving Nuclear Systems, NAS, (1970)
- Radiobiological Factors in Manned Space Flight, NAS, NRC, (1967)

## 16.0 Thermal (Burnett)

There are two main considerations regarding temperature exposure to the crew. These are touch temperature and the environmental temperature.

*Touch Temperature*
The lower temperature limits for surfaces continuously touched by the bare skin are controlled by the dew point and the variables listed above???.

Surface touch temperature design requirements for minimizing crewmember discomfort and injury are as follows:
**a.** To prevent tissue burns, the maximum allowable surface temperature for continuous contact with bare skin shall be 45°C (113°F). Objects at temperatures in excess of this can be touched safely, depending on the variables listed above????, as long as skin temperature is not raised to this level during the period of contact.

**b**. Incidental or momentary (less than 1 second) bare skin contact with surface temperatures from 46° - 49°C (114° - 120°F) is permissible. Warning labels shall be provided to alert crewmembers to these excessive temperature levels. Guards or insulation shall be provided to prevent crewmember contact with surface temperatures.
**c.** For cold surfaces that must be touched continuously or incidentally with bare skin, the minimum temperature shall not be below 4°C (39°F). Where contact with surfaces below this limit is required, adequate warning labels and protective equipment are required.

The discomfort temperatures for the hands are 68 °F and for the feet are 74 °F. The temperatures associated with pain and numbness for the hands are **50** °F and for the feet are 55 °F. **I**f the surface temperature of the hand falls below 12° - 14°C (54° - 57°F), manipulative ability begins to fail. As the hand temperature drops lower, more serious loss of manipulation ability occurs, partly from stiffness and partly from the loss of tactual sensitivity.

*EVA Touch Temperature*
EVA touch temperatures and pressures are as follows:
**a**. EVA Space Suit - The EVA suit shall maintain space suit internal surface temperatures between 10°C (50°F)??????? and 43°C (110°F).
**b**. EVA Glove - ~~The EVA glove shall provide the above protection during the subsequent to the period that the external surface of the glove is loaded to 52 mmHg???????? (1.0 psi) for 0.5 minute by an object with a surface temperatures between -120°C (-185°F) and 113°C (+235°F).~~

EVA glove materials and skin contact limits permit the safe handling of items at temperatures of -195°F to +240°F for 30 minutes with a 1 psi contact load.

*Thermal Environment*
The productivity of the crew of a space module is strongly influenced by their comfort and health. The thermal environment, consisting of temperature, pressure, humidity, and airflow conditions, is one of the most significant factors of those that determine crew comfort.

The cabin heating, circulation, and cooling systems need to be designed to maintain human comfort by controlling the atmospheric parameters of gas temperature, velocity, pressure, and humidity. Radiant heat sources must be identified and their impact on comfort assessed and controlled. The combined effects of these factors in conjunction with metabolic level and clothing worn by the crew (factors that affect skin temperature and sweat rate) largely determine comfort level.

Discomfort will tend to be more of a problem as mission length increases. The activities expected will likely be more varied and include a variety of levels of physical activity, including mandatory physical exercise. Under microgravity conditions, sweat does not drip from the body but tends to sheet on the skin and also form ringlets around the neck. Therefore, sweat removal and collection is required in the exercise area.

Thermal comfort can be defined several ways. The simplest is that condition of mind which expresses satisfaction with the thermal environment.

The comfort zone is defined as that range of environmental conditions in which humans can achieve thermal comfort, and is affected by the work rate, clothing, and state of acclimatization. The comfort zone does not include the entire range of conditions in which humans can survive indefinitely: this is a larger zone that might require active sweating or shivering, responses initiated by elevated or lowered core temperatures.

Normal atmospheric parameters for thermal comfort are :

55°F for crew workloads of 1000 BTU/hr
70 - 80°F when workloads are minimal at 300 - 600 BTU/hr
~50% humidity normal (**TBD**% humidity in the suit)

### *Human Performance in Hot Design Considerations*
The principal effect of a microgravity environment on heat transfer is the loss of natural convection, i.e., warmer air will not naturally rise. All convection under these conditions must be forced through the use of fans or blowers.

Performing heavy work results in elevated skin temperature followed by elevated body core temperature. vasodilatation and sweating commence, but cannot completely compensate for the heat load on the body. As the core temperature continues to rise, the heart rate increases and eventually may reach 70 beats per minute (or more) above normal. As the body continues to store heat, the individual may suffer from heat exhaustion. This is characterized by hypertension, difficulty with breathing (dyspnea), confusion, and fainting.

A person performing moderate or heavy work will develop higher core temperatures before onset of heat exhaustion. Occasionally, people hard at work in the heat experience almost none of the above symptoms and suddenly faint or, in some rare instances, go directly into heat stroke.

### *Human Performance in Cold Design Considerations*
In a cold stress situation, the body will rapidly reduce peripheral circulation in an attempt to conserve core heat. As the core and skin temperatures continue to drop, shivering begins and discomfort is continually present. Eventually shivering may become violent and uncontrollable. As the core continues to lose heat, shivering eventually lessens, then stops altogether. At this point, complete loss of thermoregulation is imminent. Death, however, may not come quickly. The core temperature can be drastically reduced, to 26$^{o}$C (78.6 $^{o}$F) or lower, with the body still surviving. With such extreme cooling of the core, death can occur when attempts are made to rewarm the body, cardiac fibrillation being the common cause of death.

A hypothermia victim becomes critical when the core temperature drops to about 35$^{o}$C (95$^{o}$F). The environmental indices used for heat exposure are not considered appropriate for cold because humidity is not a factor because air saturated at 0$^{o}$C (32$^{o}$F) holds only 1/5 of the water vapor as air saturated at 27$^{o}$C (80$^{o}$F).

In cold air, even a moderate air velocity will dominate other modes of heat transfer from exposed skin. In addition, the effect of moderate air velocity is only applicable to exposed skin; there is little effect on clothing up to velocities of 10-15 m/s, (32.8 - 49.2 ft/sec). Above this limit, the effects are complex; the principal danger is the formation of local cold spots on the exposed side of the body, resulting in excessive heat loss from small areas.

The final decrement is caused by the loss of brain functioning due to a drop in core temperature. The brain loses the capacity for cognitive functions if its temperature drops much below 34$^{o}$ - 35$^{o}$C (93$^{o}$ - 95$^{o}$F) even though the body is still capable of responding to instruction.

There will be no cryogenic hibernation for the crew but refrigerated storage of deceased crew members may need to be considered.

### *Special Ventilation & Metabolic Heat Removal Design Considerations*
The requirements for manned space module ventilation cannot be based on ground-based systems due to an absence of connective air flow. The primary reason for specifying air velocity limits is to extend the range of acceptable environments for the crewmembers.

The amount of air required in any region of the cabin depends on the number of crew present and on their work activity. The recommended amount of cabin air for adults engaged in moderate physical activity ranges from 2.4 - 14.2 liters/ sec (5 to 30 ft$^3$/min) per person, with approximately two-thirds of this being fresh revitalized air. In a fan ventilated pressurized suit, the flow rate must be 6 ft$^3$/min.

Special consideration in a space module should be given to the following areas:

a. Exercise Station - This area should have the capability for adjustable airflow controls and added ventilation capacity in order to facilitate the transfer of heat from the exercising crewmember's body to relieve sweat accumulation. Individual airflow units with air temperature control will help the crewmember match the airflow to the activity. The direction of airflow should not blow sweat into other station areas, particularly eating or sleeping stations, and should blow over the entire body, not just one part.

b. Sleeping Station - Individually adjustable airflow controls are desirable (allowable airflow rates are shown in Figure 5.8.3.1-1).

c. Eating Station - Airflow should not blow loose morsels of food away from crewmembers so swiftly that they cannot be recovered (allowable airflow rate is shown in Figure 5.8.3.1-1).

d. Ventilator Intakes - Ventilation system intakes should be accessible to crew for recovery of lost objects. Airflow in the vicinity of the inlets should not exceed 0.2 m/sec (40 ft/min).

The ventilation rates used in the cabin should be sufficient to control local air contamination by body products or from noxious substances in the compartment. The cabin ventilation airflow should be sufficient to dilute contaminants and divert them from the crewmembers.

***Thermal Monitoring and Control Design Requirements***

The following requirements shall apply to the monitoring and control of the space cabin thermal environment:

a. Monitoring of Thermal Environment -

1. Monitoring of cabin temperature and relative humidity shall be provided.
2. Monitoring of the thermal environment shall be fully automatic. The number, type, and location of temperature sensors and the frequency of monitoring shall be such as to ensure measurement of representative cabin temperature and to allow stable control of those temperatures.
3. Visual and audible alarms shall be automatically initiated when thermal parameters exceed the limits given in Figure 5.8.3.1-1.

| Parameter | Units | Operational | 28-day emergency |
|---|---|---|---|
| Temperature (1) | °F | 65-80 | 60-85 |
| Dew point (2) | °F | 40-60 | 35-70 |
| Ventiliation | ft/min | 15-40 | 10-200 |
| | | SI units | |
| Temperature (1) | °K | 292 300 | 289 303 |
| Dew point (2) | °K | 278 289 | 274 294 |
| Ventilation | m/sec | .08 .20 | .05 1.0 |
| Temperature (1) | °C | 19 27 | 16 30 |
| Dew Point (2) | °C | 5 16 | 1 21 |

Reference: 5, Figure 83, Page 302
324, Table 2-9

Notes:

(1) In the operational mode temperature will be selectable ±1.1 °C (±2 °F) throughout the range
(2) Relative humidity shall be within the range of 25-75 percent

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*Figure 5.8.3.1-1. Atmosphere Thermal Comfort Requirements*

b. Adjustment of Thermal Environment by the Crew - Crewmembers shall be provided with controls that allow them to modify temperatures, humidity, and ventilation rates inside the space module within the ranges for these parameters as specified in Figure 5.8.3.1-1.
c. Sleep Compartment, Personal Hygiene Area, and Waste Management Compartment Thermal Environment Controls - Temperature and ventilation shall be maintained in each of the private crew quarters, the personal hygiene area, and the waste management compartment, and shall be controlled in each of these areas within the range of these parameters as specified in Figure 5.8.3.1-1.
d. Portable Fans - If activity stations are isolated from the module air circulation systems, auxiliary airflow and/or portable fans shall be provided.
e. Exercise Station Perspiration Control - Each exercise station shall be provided with a method of sweat removal and collection.

References:

Eckart P., *The Lunar Base Handbook*, Space Technology Series of NASA and US Air Force (1998).

NASA, *Man-Systems Integration Standards*, NASA STD-3000, Volume 1 Rev. B, NASA Johnson Space Center (1995).

Webb, P., Ed., *Bioastronautics Data Book*, NASA SP-3006, National Aeronautics and Space Administration, Washington, D.C. (1964).

## 17.0 Toxicology and Contamination Limits (RKF)

Currently documented limits for gaseous contaminants can be obtained from SMAC specifications. Normal atmosphere scrubbing, sensing and off-nominal cleanup provisions are required. For representative limits and metabolic generation rates, refer to Table XXXVI in the US Segment Specification of SSP-41162. Airborne microbes shall be monitored and limited to 1000 CFU's per cubic meter. Airborne particulates shall be limited to an average of 100K particles per ft3 with a peak of less than 2M particles per ft3 for sizes ranging from 0.5 microns to 100 microns. (RKF – SSP-41162)

## 18.0 Sharp Edges, Pinching/Trapping and Electrical Shock

**Deleted**

## 19.0 Food, water, and waste per person per day (Stilwell-food; Tri-water; Joshi-waste)

**Water**

Crew water provisioning requirements can be divided into potable (drinkable) water and hygiene water requirements. Potable water is used for crew drinking, food preparation needs (typically food rehydration), and oral hygiene. Crew requirements for potable water are as follows:

- Normal operational rate: 5.16 kg/person/day (11.35 lbs/person/day)
- Degraded/emergency rate: 2.84 kg/person/day (6.26 lbs/person/day)

Crew potable water requirements also include providing water sources of different temperatures, as follows:

- Cold water: 4 deg C +/- 3 deg C (40 deg F +/- 5 deg F)
- Ambient water: 21 deg C +/- 5 deg C (70 deg F +/- 10 deg F)
- Hot water: up to 65.6 deg C (150 deg F)

Crew requirements for hygiene water are as follows:

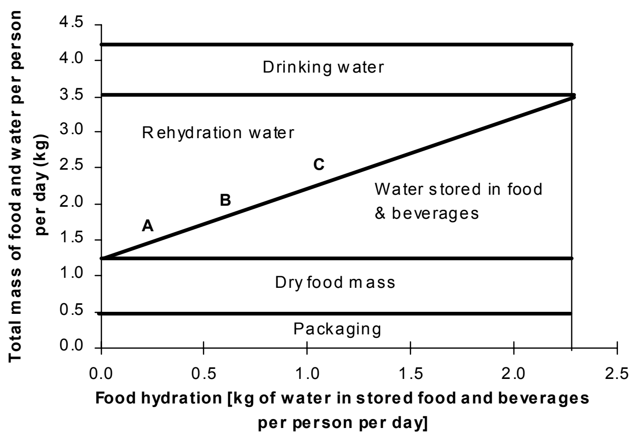
- Normal operational rate: 23.4 kg/person/day (51.5 lbs/person/day)
- Degraded rate: 8.18 kg/person/day (16.0 lbs/person/day)
- Emergency rate: 5.45 kg/person/day (12.0 lbs/person/day)

Crew hygiene water temperature must be adjustable from 21 deg C (70 deg F) to 45 deg C (113 deg F).

**Food (D. Stilwell)**

For a 6 crew, 500 day surface stay on Mars, 6900 kg of food consuming 22.4 $m^3$ are required (if we assume a Shuttle-like food system). Overall Mission Mass is reduced by the relatively high dehydration of Shuttle-like foods and by using recycled water to rehydrate foods.

**A is a fully dehydrated system (not practical)**
**B is a Shuttle-like, heavily dehydrated food system**
**C is an ISS-like food system**




**Food System (J. Joshi)**

The food system model described below is developed on the basis of the following five reference mission scenarios. These are the possible scenarios where there will be marked differences in the amount and composition of the food system used by the crew of six.

Some of the commonalties associated with the food system model are as follows:

- The food system will be free of microbial contamination. Microbial growth can adversely affect food safety. It can also affect the quality of the food system by creating changes in color, texture, and flavor.
- The food system will provide adequate nutrition for long duration space missions. The crew food energy requirement will depend on the crew themselves and the amount of physical work that they perform. Extravehicular Activity (EVA) requires additional food due to the increased physical activity involved.
- The food system will be highly acceptable and varied. Food quality can have a tremendous impact on crew morale and performance.

As the length of the mission increases, the dependence on prepackaged food items will decrease and the dependence on cropped based food items will increase.

**Scenario 1 - Transit Portion**
It is approximately a 180 days transit from Earth to Mars each way. The food items in the Transit Food System will be prepackaged foods that will probably resemble the products used on Shuttle and International Space Station (ISS). The preservation methods currently used for the Shuttle and International Space Station are thermal processing, freeze drying, irradiation, intermediate moisture foods.

One of the biggest challenges for the transit portion will be to provide acceptable food with a shelf life of 3 – 5 years (Perchonok et al.). The packaging system requires further consideration. It will need to be compatible with the processing and storage conditions, volume constraints and requirements from the solid processing system. It is estimated that the waste generated by the packaging will be a major contributor to the total waste produced during transit.

**Scenario 2 – Independent Exploration Mission (Salad Machine)**
The stay on Mars will be approximately 600 days. A single Mars Transit Vehicle will be used to get to and from Mars. The Combo Lander vehicle contains a habitat and the ascent vehicle. The habitat is destroyed when the ascent vehicle leaves Mars. The Independent Mission could be used to test food growth by use of a Salad Machine. The fresh tasting salad crops will provide variety in the menu, texture, and color. This variety should provide increased psychological benefit.

The food system will be primarily the prepackaged food system with the addition of salad crops. The challenge remains to develop an acceptable food system with a shelf life of 3 – 5 years. Food packaging will be the main source of waste. The food system will use minimal water and power during this mission.

**Scenario 3 – Concentrated Exploration Mission (One Growth Chamber)**
The stay on Mars will be approximately 600 days. Since the Concentrated Mission promotes building up the infrastructure, the possibility of having a plant chamber to grow food becomes possible. This chamber would be responsible for growing more than just salad crops, but packaged food would still be the primary diet. As more crops become available, the food system will replace some of the prepackaged food with food that will be prepared from the ingredients processed from the harvested crops.

The food system will maximize the use of the crops that are grown. The food system will design and develop food processing procedures and equipment for converting the crops to bulk ingredients. These technologies must satisfy mission constraints, including maximizing safety and acceptability of the food and minimizing crew time, storage volume, power, water usage, and the maintenance schedule (Vodovotz et al., 1997).

**Scenario 4 – Extended Base (Combination menu)**
This scenario mimics an Extended Mars Base. It involves a stay of more than 10 years. This configuration grows a multitude of plants but still relies on packaged food for more than half of the diet. The food system will utilize food processing procedures and equipment for converting the crops to bulk ingredients. These food products may be stored or used immediately, together with ingredients supplied from Earth and prepared to provide food.

The food system must balance the constraints of the crop varieties and the requirements of making the crew meals (JSC, 2000). Crop variation (quality, crop yield, and nutrient content) is expected as a consequence of water recycling of the hydroponic solution. A variation of nutrients in the growing solution will be reflected in the harvested crops' composition and, consequently, it might affect the functionality of the ingredients produced and their performance in the final food products (both processing conditions and product properties).

**Scenario 5 – Extended Base (All plant menu)**

Again, this scenario mimics an Extended Mars Base with a stay of more than 10 years. This configuration tries to rely primarily on plants for the majority of the diet (approximately 90% of the food, by dry mass).

The food system will consider the constraints of the other systems within the base. The food system must integrate with the air revitalization system, water recovery system, biomass system, solid processing system, and thermal control system. The food system will consider the availability of power, volume, and water availability as the entire food system is developed.

Crew time will increase as the food processing tasks increase as well as the food preparation time.

**Food System Model**

The food energy requirement of the crew will depend on the crew themselves, their lean body mass in particular, and the amount of physical work they are required to perform. Extravehicular activity (EVA), for example, requires additional food compared with crews conducting only intravehicular activities (IVA) because more physical work is typically associated with an EVA.

The caloric requirements for the food system are calculated based on the World Health Organization (WHO).

Men (30 - 60 years): Activity(1.7)* (11.6W + 879) = kcal/day required
Women (30 - 60 years): Activity(1.6)* (8.7W + 829) = kcal/day required

W = weight in kg
Activity level ranges from 1.0 to 2.0, medium activity level assumed

This document assumes an average body mass of 70 kg, and a caloric requirement of 1.720 MJ/person day. A crew of six is also assumed.

Crew Time

Energy and packaging requirements will be technology specific. Crew time requirements will depend on the form in which food is shipped and its preparation requirements. Crew time required for food preparation during Space Transportation System (STS, or Shuttle) missions is 45 – 90 minutes per day for a crew of up to six. This approach uses individually packaged servings.

Hunter (1999) provides another estimate of crew-time for food preparation. Hunter's model assumes that each crewmember eats ten different food dishes per day. For a crew of six, each dish prepared using ingredients provided by bioregenerative methods requires 15 to 45 minutes each, while each dish taken from resupplied stocks requires an average of 6 minutes to prepare based on Lane (1999). Assuming that meals prepared using bioregenerative methods each require 30 minutes on average to prepare, a diet based on crops grown on-site would require 5.0 ch/d or 0.83 ch/cd assuming a crew of six. Daily meals prepared completely from resupplied foods would require 1.0 ch/d or 0.17 ch/cd. Assuming five dishes are prepared from crops grown on site and five dishes are prepared from resupplied stocks, daily meal preparation time would be 3.0 ch/d or 0.50 ch/cd. Kloeris, *et al.* (1998) report meal preparation time during the Lunar Mars Life Support Test Program (LMLSTP) Phase III test while using the 10-day BIO-Plex menu averaged 9 ch/d. The crew time spent on the crop processing has not been estimated but is expected to be significant.

Transit Food System

The mass of food required depends heavily on the degree of hydration. Degree of hydration is largely a function of the type of food, and the method of storage. Fresh foods can have as much as 95% water content, while dry grains can be as low as 12%.

Besides the mass of food itself, food requires packaging to protect it from degradation and contamination. This packaging includes wrapping the food itself (into individual servings, for example), stowage (e.g., within lockers), and provision of a suitable atmosphere, and other environmental conditions, and secondary structure to house the stowage. In total, these can easily add up to a mass factor of 100% of the original food mass for packaging and stowage.

Historically packaging masses are available for two applicable food systems. Bourland (1999) reports an empty locker for food abroad Shuttle has a mass of 6.4 kg. Filled, this locker holds 36 to 40 individual meals for an overall mass of 24.5 kg.

Wastage will depend on the type of food and the type of preparation, but can be quite large. For example, during the 10-day BIO-Plex menu test conducted during the LMLSTP Phase III, total waste (including preparation, plate waste, and unused left-over food) was 42% (Kloeris, *et al.*, 1998).

Typical values from the literature for food-related masses are shown in Table 1. However, Table 2 shows a larger range of masses based on historical data.

**Table 1: Food Quantity and Packaging [2]**

| | Assumptions | | | |
|---|---|---|---|---|
| **Parameter** | **lower** | **nominal** | **upper** | **Source** |
| IVA (dw) [3] [kg/cd] | 0.54 | | | Lange and Lin (1998) |
| | | 0.674 | | Bourland (1998) |
| IVA Human Metabolic Water Production [kg/cd] | | 0.335 | | derived, Lange and Lin (1998) |
| IVA [MJ/cd] | | 11.72 | | Hall and Vodovotz (1999) |
| EVA added [4] [kg/ch] | | + 0.026 | | derived, Lange and Lin (1998) |
| EVA added [3] Metabolic Water Production [kg/ch] | | + 0.016 | | derived, Lange and Lin (1998) |
| EVA added [3] [MJ/ch] | | + 0.563 | | Lange and Lin (1998) |
| Packaging [4] [kg/kg] | | 100% | | Hanford (1997a) |
| Crew time [ch/d] | 1 | | | Lane (1999), from Shuttle |
| | | 3 | | Hunter (1999); See above |
| | | | 9 | Kloeris, *et al.* (1998) from LMLSTP Ph III |

2 The listed food values are "as shipped" and before additional of any hydration fluid (water).

3 On a dry weight (dw) basis.

4 EVA requirements are in addition to any IVA requirements.

4 Packaging accounts for individual food packages, trays, food storage lockers, and other associated secondary structure.

**Table 2: Historical/Near-Term Food Masses** [5]

| Parameter | Mass [kg/cd] | Volume [m³/cd] | Comments | Water Content |
|---|---|---|---|---|
| IVA Food, dw | 0.674 | | | 0% |
| STS Food [6] | 0.8 | 0.002558 | Dehydrated | 20% |
| | 1.818 | 0.004045 | Packaged, with Water Content | |
| | 0.227 | | Packaging Alone | |
| | 1.591 | | Fresh Weight, No Packaging | 58% |
| ISS Food [7] | 2.3 | 0.006570 | Packaged, with Water Content | |
| | 1.955 | | Fresh Weight, No Packaging | 66% |

Plant Based Food System

Currently it is assumed that the crops within a biomass production chamber will be grown and harvested on a bulk basis, rather than quasi-continuously. These food products may be stored or used immediately, and together with ingredients supplied from Earth and prepared to provide food. This assumption is designed to minimize crew time requirements by making crew activities more efficient, and may be revisited when more data is available.

Hunter and Drysdale (1996) estimated the equipment mass to perform food processing for a crew of four to be about 655 kg. However this is a very preliminary estimate.

Two diets are presented below which assume differing availability of crops grown on-site. In both cases, the menus are designed to be used as a unit in order to maintain nutritional integrity. However, minor changes might include moving small amounts of crops from the list to be grown and into the resupplied mass, especially for those items like rice that are consumed as grown. Both diets are comparable in quality and acceptability to the International Space Station Assembly Complete food system.

The ALS Program defines a 20-day crew diet using crops specified as shown in Table 3. The edible masses of the main crops as harvested to support the 20-day diet are calculated per crew-day and for a crew of six people for a 20-day period. This menu averages roughly 11.72 MJ/cd, uses a wide variety of crops, and provides a high degree of closure. With respect to closure, the majority of the resupplied mass is oil that is necessary for nutritional purposes but is not produced efficiently from higher crops.

5 From Bourland (1998) and Vodovotz (1999).

6 STS food systems are provided for reference only. They do not meet nutritional requirements for long-duration space flight. (For example, while this diet meets all minimum nutritional requirements, it exceeds the limit for sodium and iron for a microgravity diet.) This food system does not use any refrigeration.

7 International Space Station Assembly Complete food system. This food is provided as 50% frozen products. For a 540 cd (six crew for 90 d) food supply, 1.84 m³ of refrigerated storage is required.

**Table 3: 20-Day Diet Using All Crops [8]**

| Crop | Average Consumption [kg/cd] | Menu Consumption [9] [kg] |
|---|---|---|
| Soybean | 0.086 | 10.4 |
| Wheat | 0.24 | 28.8 |
| White Potato | 0.20 | 24.2 |
| Sweet Potato | 0.20 | 23.7 |
| Rice | 0.029 | 3.5 |
| Peanut | 0.013 | 1.5 |
| Tomato | 0.22 | 26.6 |
| Carrot | 0.041 | 5.0 |
| Cabbage | 0.0038 | 0.5 |
| Lettuce | 0.024 | 2.9 |
| Dry Bean | 0.013 | 1.5 |
| Celery | 0.013 | 1.5 |
| Green Onion | 0.048 | 5.7 |
| Strawberry | 0.016 | 2.0 |
| Peppers | 0.049 | 5.9 |
| Pea | 0.0075 | 0.9 |
| Mushroom | 0.0011 | 0.1 |
| Snap Bean | 0.010 | 1.2 |
| Spinach | 0.040 | 4.8 |
| **Crop Sub Total** | **1.25** | **150.7** |
| Water [10] | 2.20 | 263.3 |
| Resupplied Food Stuffs [11] | 0.37 | 44.6 |
| **Total** | **3.82** | **458.6** |

8 From Hall and Vodovotz (1999)

9 Basis: Six crew over twenty days.

10 Water for hydration, cooking, and food preparation only. Water for clean-up is not included. Water tankage is not included.

11 Oil is included as resupply. No frozen or refrigerated foods are assumed for this calculation. Packaging is not included. Resupplied food is about 20 percent moisture by mass.

A second 20-day crew diet is presented in Table 4. Again the edible masses of the main crops as harvested to support the 20-day diet are calculated per crew-day for a crew of six people for a 20-day period. This menu also averages 11.72 MJ/cd. Unlike the previous formulation, this diet grows only salad and carbohydrate crops on-site because they are the most efficient of the higher plants considered here. Most protein is resupplied primarily in the form of shelf-stable meat for this diet.

**Table 4: 20-Day Diet Using Salad and Carbohydrate Crops** [12]

| Crop | Average Consumption [kg/cd] | Menu Consumption [9] [kg] |
|---|---|---|
| Soybean | n/a | n/a |
| Wheat | 0.22 | 25.8 |
| White Potato | 0.17 | 19.8 |
| Sweet Potato | 0.18 | 21.5 |
| Rice | n/a | n/a |
| Peanut | n/a | n/a |
| Tomato | 0.21 | 24.6 |
| Carrot | 0.040 | 4.8 |
| Cabbage | 0.0025 | 0.3 |
| Lettuce | 0.021 | 2.6 |
| Dry Bean | 0.013 | 1.5 |
| Celery | 0.0075 | 0.9 |
| Green Onion | 0.034 | 4.1 |
| Strawberry | n/a | n/a |
| Peppers | 0.031 | 3.8 |
| Pea | 0.0038 | 0.5 |
| Mushroom | 0.0013 | 0.2 |
| Snap Bean | 0.010 | 1.2 |
| Spinach | 0.040 | 4.8 |
| **Crop Sub Total** | **1.0** | **116.4** |
| Water [13] | 2.1 | 253.7 |
| Resupplied Food Stuffs [14] | 0.5 | 57.5 |
| **Total** | **3.6** | **427.6** |

12 Oil is included as resupply. No frozen or refrigerated foods are assumed for this calculation. Packaging is not included. Resupplied food is about 40 percent moisture by mass. Resupplied food includes meat.

13 Water for hydration, cooking, and food preparation only. Water for clean-up is not included. Water tankage is not included.

14 Oil is included as resupply. No frozen or refrigerated foods are assumed for this calculation. Packaging is not included. Resupplied food is about 20% moisture by mass.

**Major Research and technology development issues in the food system:**

1. Shelf life of 3 – 5 year for the prepackaged food items/ Development of packaging materials that are compatible with the processing and storage conditions, volume constraints

   Shelf life can be defined as when the food is no longer safe, when it is no longer acceptable, or has lost a significant amount of nutrition. Most prepackaged food items do not have a shelf life of 3 – 5 years. Current and new food preservation techniques should be considered which would maximize safety, acceptability, and nutrition while maintaining the 3 – 5 year shelf life.

   Current and new packaging materials, which have minimal oxygen and moisture permeability while being low in mass, need to be determined. If thermal processing is used, then the packaging must be capable of withstanding high temperatures. The packaging material and seals must have enough strength to withstand the pressure changes during launch.

2. Determination of the functionality of the hydroponically grown crops and how the functionality relates to food processing

   Crop variation (quality, crop yield, and nutrient content) is expected as a consequence of water recycling of the hydroponic solution. A variation of nutrients in the growing solution will be reflected in the harvested crops' composition and, consequently, it might affect the functionality of the ingredients produced and their performance in the final food products (both processing conditions and product properties). For example, it is expected that the protein content of the hydroponically grown wheat will be higher. The higher protein content may cause a need for increasing the water or yeast level of the dough. It will also affect the quality of the bread and pasta produced from the wheat flour.

   Testing methods will need to be developed to predict the ingredients' functionality based upon their proximate analysis and, consequently, modification of the food preparation procedures will need to be developed and implemented.

3. Develop food processing equipment that has minimal mass, volume, and water usage. The equipment should minimize waste generated and be easily sanitized. Crew time should be kept at a minimum.

   The salad crops will include carrots, tomatoes, lettuce, radish, spinach, chard, cabbage, and onion. Later crops that will be grown are white and sweet potatoes, wheat, soybeans, peanuts, rice and dried beans.

   In order to keep volume and mass at a minimum, the food processing equipment should be multipurposed. An example of this equipment is the Soymilk, Tofu, Okara, and Whey Processor (STOW). The STOW can be used to process soybeans into all usable ingredients. The STOW, with minimal changes, will produce silken or regular tofu that is soft, firm, or extra firm in texture.

   Other possible pieces of food processing equipment are the gluten/starch separator, dehuller/floater, tempeh processor, grain mill, steamer, expeller, and extruder. In addition, several COTS items have been identified. They are combination microwave/convection oven, dehydrator, bread maker, pasta maker, juice/pulper, food processor, bagel maker, blender, rice cooker, scale, and dryer/oven.

   Water usage should be kept at a minimum. The equipment will be designed to use minimal water during food processing and clean-up. Since commercially available food processing equipment does not have the requirement of minimizing water usage, the food system will have to significantly modify existing equipment. If the commercially available equipment cannot be modified, the food processing equipment will be redesigned.

The wastewater should be kept at a minimum also. Since the wastewater may have a minimum of reusable nutrients in it, the wastewater will need to be recycled several times to insure that the maximum amount of nutrients has been recovered from the water. Air contamination and noise will also be kept at a minimum.

Crew involvement with preparing, operating, monitoring, cleaning, dis-assembling, and storing the equipment should be minimized to allow for more crew time in conducting experiments or collecting data. For this reason, the food processing equipment should be designed to be highly automated, and crew interaction time was minimized whenever possible.

Highly automated equipment does present several concerns that should be taken into account. One concern is that of power failure. Because the crops produce the bulk of the food during the later mission scenarios, the capability to process food during power failure is a must. The equipment should be designed so that manual operation is possible. The equipment should not be so complicated that the crew require intense technical expertise of the process.

4. Determine how to relate the psychological issues of food acceptability, variability, and menu cycle to the performance of the crew.

   Palatability plays a psychological as well as nutritional role. The isolation, confined environment, absence of family, reduced recreational options, monotonous daily routines and other stresses of living within the harsh environment of another planet for eighteen months will have adverse physiological and psychological effects upon the crew. Physiological effects include muscle atrophy, bone loss, cardiovascular de-conditioning, and electrolytic shifts. Psychological stresses can manifest themselves in a variety of emotional and physiological symptoms, such as irritability, decreased concentration, depression, decreased absorption of nutrients, and a diminished immune system. The effects of these stresses can be alleviated by positive influences of the environment upon the crew. With limited hedonic pleasures, food is expected to become the central thread of the social interactions among the crew, and its psychological benefits will prove to be quite significant to the mental health of the crew.

   A menu with varied colors and textures will aid in increasing the acceptability of the food system. A menu cycle of 20 days or more will also aid in minimizing menu fatigue.

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(M. Rudisill Input)
Food is a primary habitability concern. On short-duration missions, the crew can essentially "snack" around work activities. On long-duration missions of many types, food takes on major significance, both for its sensory qualities and for the social (and off-work) time associated with meals. Food also has strong biomedical aspects (keeping the crew healthy). Taste is affected by space. Problem in spacecraft -- cannot be resupplied with fresh food (as ISS and Mir), should consider providing capability for growing some fresh food (also good psychologically).

**Waste (Background)**

The waste model described below is developed on the basis of the following five reference mission scenarios. These are the possible scenarios where there will be marked differences in the amount and composition of waste produced.

Some of the commonalties associated with the waste model are as follows:

- The amount of fecal material produced will be the same (no significant difference in terms of the amount produced, till the food closure is 100%);
- The amount of paper, tape, filters and miscellaneous wastes are assumed to be the same (an element of caution needs to be exerted while making these assumptions as the actual amount of paper in long-duration missions may be significantly less by using electronic media).

As the length of the mission increases, the increase in inedible plant biomass will be the most significant difference attributable to the waste composition. Although there are differences in the harvest indices of salad and staple crops, it is reasonable to assume a harvest index of 50% for the purposes of waste processing. The amount of inedible plant biomass will increase with increased closure of food.

For the following scenarios, the assumption that no useable natural resources are available shall be made (this is a worst case situation as there will probably be a minimal amount of certain natural resources available for use, e.g. regolith, atmospheric make up gases).

**Scenario 1 - Transit Portion**
Approximately 180 days transit from Earth to Mars each way. No food grown. Since food is not grown, the primary waste will probably be packaging. $CO_2$ is not needed, nor is salt recovery. Water is probably the only resource that might be desired.

Since food is not grown, the primary waste will probably be packaging.

**Scenario 2 – Independent Exploration Mission (Salad Machine)**
Approximately 600 days stay on Mars. A single Mars Transit Vehicle would be used to get to and from Mars. The Combo Lander vehicle contains a habitat and the ascent vehicle. The habitat is destroyed when the ascent vehicle leaves Mars. The Independent mission could be used to test food growth by use of a Salad Machine.

At this low food growth, humans provide more than adequate $CO_2$ to allow the plants to grow. Packaging will be the main source of waste. The resources that will want to be recovered are water and possibly salts.

**Scenario 3 – Concentrated Exploration Mission (One Growth Chamber)**
Approximately 600 days stay on Mars per mission. Since the Concentrated mission promotes building up the infrastructure, the possibility of having a plant chamber to grow food becomes possible. This chamber would be responsible for growing more than just garden crops, but packaged food would still be the primary diet.

Packaging will be the main source of waste although inedible plant mass begins to be significant.

**Scenario 4 – Extended Base (Use all plants menu)**
This scenario mimics an Extended Mars Base. It involves a stay of more than 10 years. This configuration grows a multitude of plants but still relies on packaged food for more than half of the diet.

The amount of $CO_2$ from the crew is close to the level the plants need. Depending on the exact mix of crops, there may be a surplus or a deficit in $CO_2$. If a deficit exists, processing for $CO_2$ may be necessary. Recovery of salts is probably also a needed resource. Water should be recovered if possible (Plants at this growth might recycle most of the water).

**Scenario 5 – Extended Base (All plant menu)**
Again, this scenario mimics an Extended Mars Base with a stay of more than 10 years. This configuration tries to rely primarily on plants for the majority of the diet. This will yield an upper limit of the amount of inedible mass that needs to be handled.

$CO_2$ is a needed resource and so are the salts. Water should be recovered if possible (Plants at this growth might recycle most of the water).

**Waste Model**

Based on the above mentioned constraints for each of the five scenarios an envisioned waste model is presented in the following table. One important assumption made was that the packaging material quantity would apply to the all supplied reference mission (number 1) and would be scaled to the other missions based on the amount of supplied food.

The waste model is summarized below for a crew of 6.

| **Units are Kg/day (based on 6 person crew)** | | | | | |
|---|---|---|---|---|---|
| Waste Component | Transit, All Packaged Food | Independent Exploration, salad crops grown | Exploration Mission, Low carbohydrate diet | Extended Base, All plants menu | Extended Base, All plants menu |
| Dry Human Waste | 0.720 | 0.720 | 0.720 | 0.720 | 0.720 |
| Inedible Plant Biomass (1) | 0.404 | 1.874 | 5.507 | 7.486 | 13.787 |
| Trash | 0.556 | 0.556 | 0.556 | 0.556 | 0.556 |
| Packaging Material (2) | 7.908 | 7.122 | 5.866 | 4.341 | 1.185 |
| Paper | 1.164 | 1.164 | 1.164 | 1.164 | 1.164 |
| Tape | 0.246 | 0.246 | 0.246 | 0.246 | 0.246 |
| Filters | 0.326 | 0.326 | 0.326 | 0.326 | 0.326 |
| Miscellaneous | 0.069 | 0.069 | 0.069 | 0.069 | 0.069 |
| **Total** | **11.39** | **12.08** | **14.45** | **14.91** | **18.05** |
| Grown food | 0.000 | 1.740 | 6.000 | 7.500 | 14.172 |
| Packaged food | 4.044 | 3.642 | 3.000 | 2.220 | 0.606 |
| Mission Duration | 180 days | 600 days | 600 days | 10 years | 10 years |

Refer to Appendix C for the details of each waste component.

**Choice of waste processing technologies for resource recovery:**

Waste processing and resource recovery will be dictated by the following:

- Mission duration;
- Planetary protection;
- Biomass production;
- Resource availability;
- Safety.

As an example transit missions would require compaction and sterilization of wastes and water recovery. The need to recover resources for plant growth would be unessential. However, some pre-processing technologies for shredding the wastes would be useful to make water recovery more efficient. The same pre-processing technologies could be applicable on planetary missions.

Resource recovery from wastes for plant growth would not be essential till grown foods satisfy more than 50% of the nutritional requirements. At that point the choice of technologies would depend on the available energy, stowage volume of the habitat and the plant growth systems (hydroponic/ solid substrate).

Planetary protection issues will be very important in determining the choice of technologies. For instance, complete mineralization of wastes may be compelled by restricted dumping/storage and not by resource recovery needs. This may compromise the economics of a mission.

**Major Research and technology development issues in solid waste management:**

Containment, sterilization of wastes
Development of high fidelity systems to satisfy the different constraints of the various missions
Develop multi-functional systems that can be used in these missions
Systems models to identify the mission resource recovery needs
Integration of various the waste processing subsystem with the water recovery and air revitalization subsystem.

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## 20.0 Hygiene and clothes (Stilwell)

**TBD**

Personal Hygiene (M. Rudisill Input)
Hygiene facilities take on added importance on long-duration missions. Acceptability over long durations? Multicultural crews? Cleaning up after exercise? May need to be able to do laundry.

## 21.0 Space Medicine: Routine and Emergency Medical Care (Stilwell and Mueller)

Space medicine is a rapidly evolving multidisciplinary specialty dealing with the medical problems associated with human spaceflight. It is difficult to ensure the health, safety and performance of humans in space. Microgravity has considerable physiological effect on humans, including space motion sickness (SMS), neurovestibular effects, cardiovascular deconditioning, musckuloskeletal deconditioning, and psychological effects. The cabin environment may expose crew to hypoxia, decompression, toxic releases, extreme temperatures (Apollo 13), radiation and so on. Confinement, isolation, a difficult workload, stress, danger and noise environments can create difficult psychosocial adaptation problems. Medical emergencies may include burns, trauma, cardiac life support, infection, food poisoning and a host of other injuries.

Current data suggests that there is a 6% chance per year that a given ISS crewmember will develop a significant medical condition requiring evacuation. There is a 1% chance per year that this situation will be life threatening. Medical evacuation from space is not unknown. In 1976 the Salyut 5 station was abandoned 49 days into a 54-day mission for intractable headaches. On Salyut 7 in 1985 a medical evacuation occurred 56 days into a 216-day mission for sepsis/prostatitis. In 1987 there was a medical evacuation from MIR 6 months into an 11 month mission for cardiac dysrythmia. Several missions have experienced various conditions that did not result in medical evacuation but could have, including spacecraft fires in 1971, 1977, 1988, and 1997, a kidney stone in 1982, hypothermia during EVA in 1985, psychological stress reaction in 1988, spacecraft depressurization in 1997, and a toxic atmosphere in 1997. Other medical events in the US space program included a rescheduling of an Apollo 9 EVA due to medical causes, type 1 Decompression Sickness in the command module pilot in Apollo, a kidney infection during Apollo 13, a cardiac dysrythmia during a lunar EVA in Apollo 15 and chemical pneumonitits on reentry during the Apollo Soyuz Test Project due to Nitrogen Teroxide inhalation. In the Shuttle program between 1981 and 1998 at least 79% of the 508 crew members reported Space Motion Sickness and 98% reported some medical symptom.

The practice of medicine in space is confounded by severe restrictions on vehicle and personnel resources. Current medical operations concepts rely on non-physician astronauts with minimal medical experience who are supported by extensive communications with Earth-based medical personnel. As we move to longer duration missions further from Earth or involve more dangerous activities such as significant "hard hat" construction activities in space, the need for more autonomous emergency medical care becomes acute. A human Mars mission, for example, would take a multicultural crew of 4 to 6 people on a 6 to 8 month journey to the red planet. Upon arriving, the crew can expect to stay about 1.5 years on the surface before returning. Communication delays of up to 40 minutes round trip make emergency support from the ground an impossibility. Assuming that a physician will be among the crew on such a mission, it is quite possible that the physician may ill or that the whole crew might be affected. Additionally, many medical emergencies normally require a team of doctors, nurses and other specialty medical professionals such as laboratory technicians, pharmacists, radiologists, and pathologists. Instead, a relatively small crew with specialties in electrical and mechanical engineering, astrobiology, geology, and other mission critical skills but little training and practice in emergency medical response will have to handle medical emergencies of all sorts under extremely stressful conditions. To make matters worse all equipment and supplies in a “space hospital” must be stowed in the tightest configuration possible, unlike a hospital emergency room where equipment and supplies are readily at hand, powered up and in a high state of readiness. Vital decisions in medical emergencies must be made quickly with little forgiveness for error. Clearly, intelligent medical systems will have to be devised to support these efforts and will have to become physician-equivalent helpers in the event of critical emergencies.

A variety of technologies related to intelligent systems in medicine are required including:

- Visual programming shells/interfaces that allow physicians and other medical experts to easily capture their knowledge for diagnostic aids, decision support tools, medical protocol control, multimedia training tools, and other support systems.
- Methods of coordinating the activities of teams, such as control through RF linked palmtop computers or other means, to ensure adequate emergency medical response.
- Methods for rapidly entering medical records and comparison with existing records for rapid diagnostic support, allowing more natural and easier ways of interacting with or accessing medical knowledge in the context of real data.
- Medical data visualization techniques that provide large quantities of complex data in easy to understand and manipulate forms, allowing questions about the data to be easily and intuitively investigated in an interactive fashion.
- The use of physiological simulation models to aid in protocol and procedure development for emergency medical response.

- The use of detailed physiological models of individual patients in decision support to allow prediction of the effect of treatments or the administration of pharmaceuticals for guiding protocol selection in particular cases.
- On-the-spot tools for providing decision support and "just-in-time" training to allow relatively unskilled individuals to perform emergency treatment that they would not otherwise be capable of performing.
- Basic tools for creating intelligent, tutoring applications that can be used to insert medical training into long term missions, especially those that use a multimedia case study approach.
- Novel automated means for delivering various aspects of emergency medical care to free up crew members to take on other tasks.

A particularly relevant application is just-in-time training for emergency medical care. For example, we could create an intelligent aiding tool that would allow people of different capabilities to run through the process of dressing wounds based on the presented problem. This approach limits information and training to the specific case at hand; there is no need to learn about minor burns if the injury involves critically burned tissues. Furthermore, training on the stabilization and treatment of such burns might be different for a physician than for a geologist. Authoring tools for such training systems would allow for easy adjustment of the difficulty of the training to the individual user's knowledge and skills.

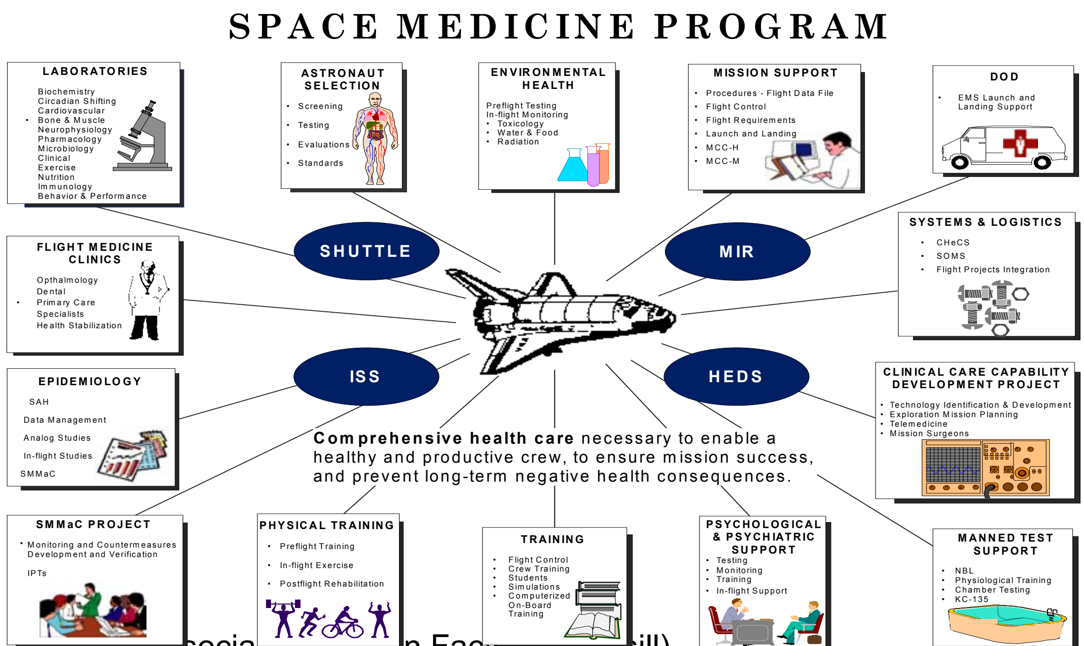
It is extremely difficult to develop a health care system that has enough supplies and equipment to handle the large number of medical conditions that might be present in a long mission. Clearly multiple instances of problem might be present across all or several crewmembers, and problems may occur repeatedly during a mission. It is not possible in a future Mars or Lunar mission, for example, to travel light. For Mars, estimates of the mass of a crew health care system per habitable vehicle are at least 1,000 kg for equipment and 500 kg for consumables, with a total volume of at least 4 m.[3] A Lunar base would have to be similarly stocked, although the possibility for Earth return should reduce the mass and volume slightly. The technologies that would need to be provided include:

***Define the statistically most probable diseases and injuries and address what it takes to diagnose and treat these. Put together a program to miniaturize the resulting relevant medical equipment***

- Non-invasive, in-vivo, biosensors and clinical laboratory equipment for monitoring blood chemistry: calcium ions, electrolytes, proteins, lipids, and hormones as well as cellular components
- Real time, in-vitro, biosensors and clinical laboratory equipment for monitoring urine, stool, sweat, exhaled gas chemistry
- Implantable/injectable/ingestable biomedical sensors.
- Long shelf life pharmaceuticals (3 years) and/or drug factory
- Telemedicine systems for orbital and near earth/moon consultation and mentoring
- Laboratory diagnostics (clinical chemistry, hematology, pathology, microbiology, hematology, endocrinology, etc.).
- Imaging diagnostics (radiographic, magnetic resonance, ultrasound, etc.).
- Non- or minimally invasive monitors (ECG, BP, $SpO_2$, HR, T, etc.).
- Equipment, devices, instruments and protocols for a in-flight cytometer, delayed type hypersentitivity test device ("skin test"), in-flight Enzyme-Linked Immunoassay (ELISA) system, in-flight blood collection and distribution system, and a cell culture and challenge system.
- Systems, subsystems, equipment, instruments, devices, and protocols to provide emergency surgery and critical care.
- Systems, subsystems, equipment, instruments, devices, and protocols to provide rescue, resuscitation, stabilization, and transport.
- Fluid therapy systems - to include infusion pumps, on-site production of sterile fluids, nutritional support, blood and blood component replacement.
- Medical waste management system.

- Advanced medical storage systems (samples, pharmaceuticals, etc.)
- Microsurgery/microtherapeutics equipment and protocols.
- Methods for monitoring the radiation environment and dose received such as an active, solid state, personal radiation dosimeter
- Radioprotectants and methods for monitoring pharmacological treatments for radiation exposure
- Methods for real time, autonomous monitoring of air, water and food for microbial and chemical contamination

The components of the current (ISS and Shuttle) Space Medicine Program are shown below.




## 22.0 Psychosocial Interaction Factors (Rudisill)

Recommendations for mission success in the area of psychosocial issues generally fall within three areas: crew performance, crew selection, and training.

**Crew Performance**:

- **Balanced Workload:** Workload needs to be managed effectively at both ends (ISS/Mars vehicle and MCC) so that there is a minimal amount of under/overloading. This includes providing rest times, days off, and breaks, and implementing crew rotation to prevent boredom.

- **Sleep**: Sleep needs to be a priority and tasks, experiments, and communications should be scheduled with the astronauts' requirements for sleep in mind. Provisions should be made for quality sleep (e.g., architectural design, quiet operations, with sleep medications, earplugs for quiet, privacy).

- **Design**: Proper crew station design needs to be followed to design effectively for physiological changes in space as well as postural changes that will occur over the duration of a long exploration mission.

**Crew Selection**:

- **Personality**: Selection criteria should include personality traits which facilitate overall crew compatibility and with MCC (perhaps MCC controllers should be subject to the same selection process as astronauts). It is assumed that those astronauts in the selection process will be highly technically qualified individuals; consideration needs to be given also selecting for appropriate personality traits. Desirable traits for an exploration crew (including multi-nationals) are: low aggression, low competitive/team player, low stress reaction, mixed-gender, and a mix of older experienced and younger less experienced astronauts.

- **Hierarchy**: A hierarchical organization of the crew must be established and honored by both crew and MCC, with ultimate decision authority with the crew side, resting on a crew leader, especially in times of crisis. This person or another appointed individual with appropriate negotiation skills also should take on the additional responsibility of speaking with MCC to provide day-to-day reports so that the entire crew's schedule need not be interrupted.

**Training**

- **Psychological emergencies**: It is necessary that all crew members be trained in medical procedures as well mediation and negotiation procedures that may be necessary for a psychological intervention or emergency on the vehicle during the mission.

- **Psychological support**: Psychological support training, differentiated from psychological emergency training by its preventative nature, is critical during pre-mission training for a long-duration space mission. Cross-training several crewmembers in the recognition of psychological symptoms is valuable prevention against a psychological emergency.

- **Psychological education for families**: NASA and the various international space agencies involved should provide the families of astronauts with the opportunity to voice their concerns. These agencies also have the responsibility and duty to identify potential problems that they will encounter with their traveling loved one and to provide a support network for them before, during and after return. Communication issues may become difficult and frustrating at times with the long distance and time delays; it is important to provide all involved with support and reassurance before, during, and after the mission. The issue of the death of a loved one while away from Earth, procedures to handle the death, and the identification of ceremony preferences should be discussed openly prior to launch.

**For additional detailed information, refer to Appendix D.**

## 23.0 Architecture (Burnett)

***We should not define the next several sections in terms of facilities. These should be defined in terms of functions and capabilities.***

The architecture of the space vessel must consider the following facilities:

**a.** Personal hygiene facility.
**b.** Body waste management facility.
**c.** Crew quarters.
**d.** Galley and wardroom.
**e.** Reduced gravity countermeasures.
**f.** Space medical facility.
**g.** Laundry facility.
**h.** Trash management facility.
**i.** Stowage.
**j.** Meeting facility.
**k.** Recreation facilities.

Other architectural considerations include the following:

**a.** Compartmental Placement
**b.** Habitable Volume
**c.** Traffic Flow
**d.** Hatches and Doors
**e.** Windows
**f.** Mobility Aids
**g.** Interior Décor
**h.** Lighting
**i.** Orientation Cues
**j.** Location Coding

ARCHITECTURE

The architecture of any space craft must consider the following architectural needs and considerations. A number of facilities are described below. Following the description of facilities are specific considerations for designing and configuring the craft.

*PERSONAL HYGIENE FACILITY*

Good grooming can enhance self image, improve morale, and increase the productivity of the crewmember. Adequate and comfortable bathing and body waste management facilities have been high on the list of priorities of participants in various space missions. Some modification of personal hygiene practices and procedures may be necessary due to equipment design limitations and water supply restrictions. Too great a modification, however, could impact negatively on crew self image and productivity. It would be unwise to expect optimum performance unless optimum conditions are provided.

This section deals with the facilities required for personal hygiene. Personal hygiene includes: Body washing (whole or partial), oral hygiene, hair cutting, grooming, shaving.

Design Considerations

The following are considerations to be made in the design of a personal hygiene facility:

**a.** Ease and Comfort of Use - Experiences with the Skylab shower design has shown that personal hygiene facilities will be less frequently used if they are awkward, uncomfortable, or take an inordinate amount of time to use.

**b.** Privacy - It is desirable to have privacy for crewmembers for whole body and partial body cleaning (including donning and doffing of clothing).

**c.** Microgravity Considerations:

1. Cleanup - In microgravity, water and debris, such as hair, do not fall to a fixed surface (such as the floor) as they do on Earth. Water and debris float. Water cannot be simply drained away and hair cannot be swept up. Collection of water and debris become both an engineering problem and an operational problem for the crewmember. Functions that require relatively little time on Earth, such as a shower, can require much more time and be less relaxing because of the cleanup requirements due to microgravity. This can impact negatively both on mission schedule and personal motivation to use the facilities. Designs should minimize the time and discomfort penalties resulting from microgravity.

**2.** Restraints - Restraints should be provided so that the crewmember does not compromise the personal hygiene operations by having to stabilize him or herself. These restraints should be compatible with the personal hygiene operation. For example, foot restraints in a whole body wash facility should not be damaged when exposed to water.

*BODY WASTE MANAGEMENT FACILITIES*

This section discusses the human factors design considerations and requirements for the collection and disposal of wastes generated by the human body. The body waste management facilities handle feces, urine, vomitus, diarrhea, menses, and other wastes. Transfer, storage, and processing of waste products are not covered in this section; only facilities that directly interface with the crew are covered.

Design Considerations
Ease of Use - The system should be simple and quick to use. The system should readily be available for emergencies such as vomiting or diarrhea. As a design goal, the facilities should be used like and require approximately the same amount of time for use as equivalent Earth facilities.

*CREW QUARTERS*
This section covers design considerations and requirements for the design and layout of private activity and sleeping quarters for an individual crewmember. Although the quarters described are basically for use in a microgravity environment, most of the considerations and requirements listed are applicable to systems in any space environment.
Individual Crew Quarters Design Considerations
The following design considerations apply to the design and layout of crew quarters.
**a.** Mission Duration and Privacy - The amount of volume required for each crewmember is dependent on the duration of the mission. As the mission becomes longer the need for privacy increases. Crewmembers sequentially occupying the same sleep space (hot-bunking) should usually be avoided. There are several design solutions for individual privacy. One of these solutions is described in this section: private quarters for individual recreation and sleeping. Other arrangements for privacy include:
**1**. Dormitory sleeping and private areas available to each crewmember.
**2.** Shared private quarters so that two crewmembers on different shifts share the same quarters.
**3.** Quarters for two individuals who want privacy (i.e., married couples).
**4.** Expanded function quarters which might include full body wash facility, waste management facility, office, private dining, or meeting facility.
Other Design Considerations
The following are design requirements for one-person individual crew quarters:
**a**. Communications - Two way audio/visual/data communications system shall be provided between the crew quarters and other module areas, and the ground. The system shall have the capability of alerting the crew quarters occupant in an emergency.
**b.** Environmental Controls - Independent lighting, ventilation and temperature control shall be provided in crew quarters and shall be adjustable from a sleep restraint.
**c.** Noise - The noise levels in the crew quarters shall be per requirements.
**d**. Compartment Size - For long duration space missions, dedicated, private crew quarters shall be provided for each crewmember with sufficient integral volume to meet the following functional and performance requirements:
**1**. 1.50 $m^3$ (53 $ft^3$) for sleeping.
**2.** 0.63 $m^3$ (22 $ft^3$ ) for stowage of operational and personal equipment.
**3.** 1.19 $m^3$ (42 $ft^3$ ) for donning and doffing clothing.
**4**. Additional free volume, as necessary, for using a desk, computer/communication system, trash stowage, personal grooming, dressing/undressing convalescence, off-duty activities, and access to stowage or equipment without interference to or from permanently mounted or temporarily stowed hardware. The internal dimensions of the crew quarters shall be sufficient to accommodate the largest body size crewmember under consideration.
**e**. Exit and Entry - The opening shall be sufficiently large to allow contingency entry by an EVA suited crewmember.
**f.** Privacy - The individual crew quarters shall provide visual privacy to and form the occupant and acoustic privacy.
**g.** Restraints - Restraints shall be provided as necessary for activities such as sleeping, dressing, recreation, and cleaning.
**h.** Windows - Window accommodations shall be provided in individual crew quarters on long duration missions.

*GALLEY AND WARDROOM*
Meals can do a lot to enhance the quality of the crewmembers' lives. In addition to satisfying hunger, mealtime can provide a chance to rest, socialize, and provide a familiar contact to normal Earth living. In addition to the boost in individual morale, there are advantages to be gained from

the social aspects of mealtime. It has been suggested that space travelers should plan to share at least one meal a day together in order to help maintain a positive group feeling.

Design Considerations

The following are considerations for the design of the space module galley and wardroom:

**a.** Food Consumption Locations - Past space flight experience is indicated that a large percentage of food is consumed at work stations remote from the food preparation area. This strongly indicates that provisions should be made for frequent consumption of food as efficiently and completely as possible at locations remote from the preparation area.

**b.** Traffic Flow - The galley and wardroom shall be configured to provide clear traffic paths for the crew to efficiently perform the following tasks:

**c.** Size of Crewmembers - Galley and wardroom hardware shall be usable by international crews and by the full size range of crewmembers.

**d.** Restraints - Restraints shall be provided for crewmembers, food, utensils, cooking equipment, and other loose items as necessary at galley and wardroom locations.

**e.** Design for Cleaning - The surfaces in the galley and wardroom shall be easily accessible for cleaning and sanitation. The surface texture shall be capable of being wiped clean. Closeouts shall be provided to preclude contamination in areas that are inaccessible.

*MICROGRAVITY COUNTERMEASURE FACILITY*

This section discusses the facilities used in a microgravity environment to combat the harmful effects of microgravity on the human body. The requirement for a microgravity countermeasure facility assumes that the mission duration will be 10 days or longer.

Design Considerations

A summary of the effects of microgravity on the human body, possible countermeasures, and considerations for the design of facilities to support these countermeasures is shown in Figure 10.8.2-1. The following is a further discussion of these considerations:

**a**. Mission Duration - This section assumes a mission duration of at least 10 days. For missions less than 10 days, an exercise facility is desirable for crew morale and well-being. The anticipated physiological decrements of a short mission can be countered by compensatory conditioning programs prior to the mission.

**b.** Multi Facility Function - The effects of microgravity can be counteracted in a number of different facilities in the space module, if such are equipped with appropriate countermeasures exercise equipment. The primary function of the microgravity countermeasure facility would be to serve as an area for exercise specific to countermeasure capability and for storage of this equipment.

**c**. Facility Location - The following considerations should be made when locating a fixed facility within the space module:

**1**. Vibration and noise - Some exercise equipment is noisy and causes vibration. This equipment should be isolated from sensitive areas such as crew quarters or sensitive workstations.

**2**. Personal hygiene area - Post exercise whole or part body washing facilities should be close to the countermeasure facility.

**3.** Galley or potable water dispenser - Liquids should be available for crewmembers during strenuous exercise.

**d.** Microgravity Considerations - The design of the countermeasure facilities should account for the effects of microgravity. Some of these considerations are listed below:

**1.** Drying of perspiration - Perspiration will not drip from the body but will pool on the body and then float into the atmosphere. Methods of eliminating perspiration before it has a chance to contaminate the module, such as absorptive clothing or a high flow level or dry air, should be investigated.

**2.** Convection cooling - In 1-G, warm air around the body will rise providing cooling. In microgravity this will not occur. Ventilation for cooling must be provided through forced air.

**3.** Debris containment - Debris, such as hair and lint, will not fall to the floor where it can be swept up. There must be a means, such as a vacuum system, to collect such material.

**e**. Exercise Equipment to be Accommodated

**1.** Strength Equipment - An isotonic strength mechanism (probably an ergometer), capable of imposing resistive forces of from 45 to 1335 N (10 to 300 lb), so that crewmembers can perform weight-lifting type exercises, shall be included

**2**. Aerobic Equipment - A minimum of one piece of aerobic exercise equipment shall be provided.

**3.** Anaerobic Equipment
**4.** Skeletal Muscle Equipment

*SPACE MEDICAL FACILITY*
This section deals with the design of a Space Medical Facility (SMF). An SMF is any area that is set aside primarily for medical treatment of crew members. The requirement for an SMF assumes that the mission duration will be long term ( in excess of 2 weeks) and that medical treatment outside the module is not immediately available. The information in this section applies to any gravitational environment, although some areas emphasize microgravity conditions and will so state. This section addresses both the environmental and physical requirements of the SMF.
Design Considerations
A SMF is a dedicated space module area that shall be set aside primarily for medical treatment of crewmembers on long term missions. Some or all of the following capabilities will be required in any given program, and specific elements will be determined by mission duration, crew size and flight characteristics.

Prior to the design of the SMF the following information must be determined:
**a**. Duration of the Mission.
**b.** Crew Statistics - The health status, age, and number of crewmembers.
**c.** Mission Activities - The nature of the activities required during the missions.
**d.** Medical Support - The availability of medical support outside the module.
This information, together with historical data on the nature and frequency of illness and injuries, will determine the size of the SMF and the specific types of equipment required. Once these decisions are made, the detail design process can begin.

The SMF must provide the equipment and supplies to perform the following functions:
**a.** Prevention.
**b.** Diagnosis.
**c.** Therapy.
Some of the equipment and supply items support two or all three of these functions.

*LAUNDRY FACILITY*
Design Considerations
**a.** Laundry Collection, Processing, and Distribution System - There are a number of different options for laundry collection, processing, and distribution. Each of these options require different human factors considerations. Some of the options and their human factors implications are listed below:
**1.** Central collection, processing, and distribution laundry area - This might save overall module volume but could result in loss of crew time to making daily trips to the laundry area.
**2.** Several small collection points and central processing and distribution area - This would increase module volume devoted to the laundry function but may improve crew efficiency. An automated transfer of dirty laundry (through conveyor or piping system) would further increase crew efficiency.
**3.** Several small collection, processing, and distribution areas - Would save crew time in collection and distribution but may require more volume and more crew time in actual laundry processing.
**b.** Noise - Laundry facilities are a potential source of high noise levels. They must be isolated or insulated as required to ensure that the noise requirements are met.

*TRASH MANAGEMENT FACILITY*
This section discusses the design of the space module trash management facility and equipment. This includes both biologically active and inactive materials. It does not include metabolic/body wastes.
Design Considerations
The following are considerations for the design of the space module trash management facilities.
**a.** Quantity and Nature of Trash - The amount and nature of the trash will depend on the nature of the mission and the design of the space module. All wrappings, etc., should be minimized and

disposables chosen for maximum efficiency and minimum residual. Some of the variables are listed below:
**1.** Number of crewmembers.
**2.** Disposable versus reusable items (clothing, utensils, etc.).
**3.** Mission duration.
**4.** Type of work performed (experimentation, processing, manufacturing, etc.).
**b.** Separation - The system may require separation of biologically active and inert trash in order to facilitate stowage and disposal. The crew may have to participate in this function.
**c**. Location of Trash Receptacles - The selection of trash receptacle types and locations must consider crew productivity. Several small throughout the module may initially save crew time but will cost time if the crew must gather the trash from the receptacles and transport it to a central receptacle.
**d**. Productivity - Trash management is not a productive crew function. Every effort should be made to automate trash management, reduce volume by compaction, and reduce manual manipulation.

*STOWAGE FACILITY*
This section covers the overall layout and location of dedicated stowage facilities inside the space module. A storage facility can be integrated with a crew station or may be a separate area apart from the normally occupied areas.
Design Considerations
The following are considerations for the design of a stowage facility.
**a**. Facility Type and Location - Items should be stored in an area as close as possible to where they are used. The following is a list of crew stations and the type of equipment that should be stored adjacent to these stations:
**b.** Environment - The environment of the storage area must not only be compatible with the stored items, but should be habitable by a crewmember that must unstow, restow, stock, and maintain the facility.
**c.** Flexibility - The stowage facility must change as the module mission and size changes. Features of the stowage facility that will accommodate change are listed below:
**d.** Central Storage Versus Distributed Storage - Ideally items would be stored adjacent to their use point. There are cases however where this is impractical. A central storage point for some items makes inventory tracking a simpler task. This might include low use items or items which are used in many different stations. In many cases a central storage and distributed storage system can be combined. This might occur in the galley where food for a single meal is stored in a pantry but the entire food supply is stored in a central facility.
**e.** Facility Entrance and Exit - The entrance and exit to the stowage facility should be designed for the crewmember carrying the stowed items. The following considerations should be made: ***This presumes there is a dedicated facility for this function. This should not be assumed.***

*MEETING FACILITY*
This section discusses the considerations and requirements for the design of a meeting facility within the space module. The wardroom can be used as a meeting facility.
Design Considerations
The following considerations should be made for the design of a meeting facility:
**a.** Capacity - The meeting facility must comfortably and safely accommodate the expected number of meeting participants. This includes the passageways to meeting facility, the size of the entry and exit, and the volume of the room.
**b.** Location - If a meeting facility is to be used often, then it should be located centrally to the space module where transit times for the participants can be minimized. The following are additional location considerations:
**1.** Waste management facility - It is desirable to have waste management facilities near the meeting facility if the meetings last more than 1 to 2 hours.
**2.** Galley - It is desirable to have availability of refreshment during extended meetings.
**3**. Sleeping or other areas sensitive to noise, light, and vibration - The activities in a meeting may be disturbing to adjacent functions. The meeting facility location should be selected with this in mind.

**c.** Location of Meeting Participants - Participants should be positioned to facilitate the various types of meetings to be conducted. This requires flexibility in the location of the furnishings and seating or restraint placement (in the case of microgravity conditions). The following arrangements are possible:
**1.** Full crew interactive discussions; large table
**2.** Small group interactive discussions.
**3.** Several small group interactive discussions.
**4.** Auditorium presentation.
**d.** Environmental Factors - The following are environmental considerations for design of a meeting facility:
**1.** Noise - The noise level must be sufficiently low to conduct meetings.
**2.** Temperature and ventilation - The temperature and ventilation control system will have to accommodate several different group sizes.
**3**. Lighting - The meeting facility lighting must allow viewing of both projected or self-illuminated displays and non self-illuminated displays.
**e.** Equipment Requirements - The meeting facility should provide equipment and equipment storage areas necessary for conduct of meetings. The design of the meeting facility should consider accommodation of the following equipment items: ***<u>The following assumes a solution and old technology.</u>***
**1.** Projection system.
**2**. Screen or central display area.
**3**. Means for meeting participants to record proceedings of the meeting.
**4.** Microphone and speakers.
**5.** Two way communication facilities for participation of persons outside the module.
**6.** Audio and visual recording and playback equipment.

*<u>RECREATION FACILITY</u>*
<u>Design Considerations</u>
The following are considerations to be made when designing a recreation facility for a space module:
**a.** Storage - There should be a location near the recreation facility for storage of games, books, audio-visual materials, and other recreational items. This storage location should have an inventory of the contents and instructions for the use of the recreational materials.
**b**. Environmental Control - Active game areas will produce heat, perspiration, and debris. Ventilation and heating must control temperature and odor.
**c**. Size - The facility shall be sufficiently large to accommodate all crewmembers scheduled for leisure activities.
**d.** Location - Recreational facilities shall be located where they do not conflict or restrict the activities of other space module functions and, conversely, they shall be located where the planned recreational activities are not compromised by other space module activities.
**e.** Window - Where feasible, an outside viewing window shall be provided for recreational purposes.

*<u>OTHER ARCHITECTURAL CONSIDERATIONS</u>*
This section discusses the placement, arrangement, and grouping of compartments and crew stations in space modules.
<u>Compartmental Placement Design Considerations</u>
Design of any system or facility should be based on the logical sequence and smooth flow of activities that are to occur in the facility. Generally, the most efficient layout is to place crew stations adjacent to each other when they are used sequentially or in close coordination. There are some limitations to this general rule, however. Adjacent positions should not degrade any of the activities in the stations, nor should the positioning degrade any of the activities in the surrounding stations. General adjacency considerations, beyond simple activity flow, are listed and discussed below.

**a**. Physical Interference - Some crew stations require a high volume of entering and exiting traffic (both personnel and equipment). Placement of these stations adjacent to each other could result in traffic congestion and loss of efficiency.
**b**. Noise - Activities such as communications, sleeping and rest, and mental concentration are adversely affected by noise. Activity centers generating significant noise levels should not be placed adjacent to those activity centers adversely affected by noise.
**c**. Lighting - Ambient illumination from one activity center may either interfere with or benefit the activities in an adjacent center. Activities that require illumination will benefit from the Activities adversely effected by light could be:
**1**. Certain experiments or lab activities such as photographic development.
**2**. Sleeping.
**3**. Use of some optical equipment (such as windows) and self illuminated displays (such as CRT).
**d**. Privacy - There are cultural and individual requirements that should be considered. Certain personal activities such as sleeping, personal hygiene, waste management, and personnel interactions require some degree of privacy. These private areas should not be placed in passageways or highly congested activity centers.
**e**. Security - Many of the experiments and production processes will be confidential to a specific industry or organization. These activity centers may require visual, audio, or electrical isolation from the rest of the space module.
**f**. Vibration - Certain personal activities, such as relaxation and sleep, will be disturbed by vibrations and jolts. In addition, many production, experimental, and control functions will require a stable and vibration-free platform. Crew stations of these types should be isolated from sources of vibration.
**g**. Contamination - Crew station activities can generate contaminants. These activities may include manufacture, maintenance, personal hygiene, or laboratories. Other crew station activities may be extremely sensitive to contamination. These activities include food storage and consumption, laboratory research, some production processes, and health care. Contaminant sources and areas highly sensitive to contamination should be physically separated in the overall space module layout.

<u>Habitable Volume Design Considerations</u>

Previous crew experience indicates that throughout long duration missions items are deployed and not effectively restowed. Furthermore, the effect of zero-G decreases the crews ability to tightly and neatly stow many items, such as wires and cables that are apt to float into usable areas.

Six hundred cubic feet (600 $ft^3$) of usable space is the minimum amount required per crewmember for long duration missions. Any amount below that will result in loss of crew productivity.

<u>Traffic Flow Design Considerations</u>

The following analytical process can help to optimize traffic flow and crew functioning:
**a**. Analyze Functions and Tasks - Determine the type and level of activity that occur at each of the crew stations and the required movement of crew and equipment between the stations.
**b**. Locate Crew Stations - Locate crew stations to minimize the traffic flow.
**c**. Design Translation Paths - Once the crew stations are located, design the translation paths for efficient traffic flow. First, design the paths to accommodate the traffic flow requirements of the worst case conditions. Then, complete the design to meet other traffic flow requirements. The following are steps for translation path design:
**1**. Define traffic flow details: number of persons, number of transits, type of packages, speed of transit, type of activity surrounding the path, etc. Be sure to identify worst case traffic flow conditions.
**2**. Accommodate possible congestion at intersections through scheduling, increase of path size, provision for visibility of crossing traffic, etc.

<u>Hatches and Doors Design Considerations</u>

The following are considerations for the location and design of hatches and doors:
**a**. Use of the Hatch or Door - The following is a list of the types of hatches and doors and some of their specific design considerations:
**1**. Pressure Hatch - Although the pressure hatch must be able to withstand high-pressure loads, it must not be too massive or difficult to operate. Due to the criticality of the pressure hatch,

operating procedures and hardware must minimize the chance of unsafe operations. Normally, the pressure hatch opening size and controls must be designed to be used by a space suited crewmember. Reliability is enhanced if hatches open toward the higher pressure volume, thus making them essentially self- sealing.
**2**. Internal Doors - Internal doors may be necessary for visual privacy, reduction of light, reduction of noise, fire barriers, and restraint of loose equipment. The configuration will vary accordingly.
**3**. Emergency Hatches - Emergency hatches are used primarily for escape or rescue. A dedicated emergency hatch should not interfere with normal activities. In an emergency, however, hatch operation should be simple and quick. Where pressure loss is a possibility, emergency hatch openings must be sized for space suits.
**b**. Opening Size and Shape - The following considerations should be observed when selecting the hatch and door opening size and shape:
**1**. Body Orientation - Frequently used hatches and doors should not require body reorientation to pass through. In microgravity conditions, this means that the opening should allow passage of a crewmember in the neutral body posture.
**2**. User Size - The size of the hatch and door opening should accommodate the largest crewmember plus any equipment to be transported.
**3**. Space Suited Crewmembers - Generally, internal doors need only be used by IVA crewmembers; in some cases, however, it may be necessary to provide opening room for passage for a space suited crewmember.
**c**. User Strength - The operating forces of the door opening system must be within the strength range of the weakest of the defined crewmember population.
**d**. Traffic Considerations - Internal doors and hatches are points of potential traffic congestion. The following considerations should be made to ease the traffic flow:
**1**. Do not place doors or hatches near a corner where a translation path junctures with another path and/or where a single path turns the corner. The doorway should be at least 1.5 m (5 ft) from the corner.
**2**. Door and hatch covers should not open into congested translation paths. Rather, they should open into the compartment.
**3**. Door and hatch openings should be sized for the traffic flow. To be efficient, a high use doorway may require an opening to accommodate more than one crewmember at the same time.

Windows Design Considerations
The following are considerations that should be observed when locating windows within the space module:
**a**. Functional Considerations - Earth/celestial observations
**b**. Traffic - The windows should be located so that use of windows will not interfere with required traffic flow.
**c**. Light and Glare - The following are lighting and glare considerations for window location:
**1**. Glare on window - Bright interior illumination could reflect from the window surface and degrade visibility.
**2**. Dark adaptation for celestial viewing - Bright interior illumination may degrade dark adaptation required for celestial viewing.
**3**. Light sensitive activities - Exterior light through windows could degrade light sensitive activities such as sleeping, use of CRT displays, or tasks requiring dark adaptation.
**4**. Natural light and calcium loss - Calcium loss from bones in microgravity is a problem of major concern. Since vitamin D obtained from certain wavelengths of natural sunlight facilitates absorption of calcium by the gastrointestinal tract, it is postulated that provided by controlled crew exposure to appropriately designed and located windows.
**5**. Destruction of bacteria with natural light - A window could be located so that the light could be used against the growth of pathogenic bacteria.
**6**. Use of natural light for illumination - A properly designed and located window can use natural sunlight as a supplementary source of internal space module illumination.

Mobility Aids Design Considerations
The following considerations should be observed when locating IVA mobility aids:

**a**. Method of Use - Previous experience has shown that mobility aids such as hand rails are not used for hand over hand translation. Mobility aids are used primarily for control of body orientation, speed, and stability. After humans gain confidence in free-flight translation, contact with planned fixed mobility aids is primarily at free-flight terminal points or while changing direction. Padding or kick surfaces should be considered at these points.
**b**. Package Transport and Mobility Aid Use - Consider the packages that the crewmembers might be carrying. One or two hands may be required to negotiate and guide the package.
**c**. EVA Use in Emergency - IVA mobility aids may have to be used by space suited crewmembers under emergency conditions. The location should, therefore, account for bulky garments that reduce joint movement and clearance.
**d**. Substitute Mobility Aids - Walls, ceilings, or any handy equipment item may be used as a mobility aid. Surfaces and equipment along translation paths should, therefore, be designed to accommodate this function.
**e**. Operator Stability - Locate restraints where it is critical that a workstation operator remain stable for task performance (i.e., view through an eyepiece, operation of a keyboard, repair a circuit, etc.).
**f**. Counteracting Forces - Locate restraints where task performance causes the body to move in reaction to the forces being exerted. For instance, a crewmember using a wrench should be restrained from rotating in an opposite direction to the applied torque.
**g**. Two Hand Task Performance - Some simple tasks can be easily performed with one hand while using the other hand for stability. More complex tasks, however, require coordination of both hands and somebody or foot restraint system may be required.

Interior Décor Design Considerations
The following are general considerations for the design of the interior decor:
**a**. Simplicity - Interior design (decor) should be simple, i.e., too many colors, complicated visual patterns, large areas of extremely saturated colors or too many fabric variations may result in visual or sensual oversaturation. Such treatment becomes an annoyance to most observers, especially over long periods of exposure.
**b**. Variety - Extreme simplicity can be carried too far. Drab, singular color or completely neutral (e.g., all gray) color schemes and smooth, untextured surfaces are monotonous and lead to boredom and eventual irritation with the bland quality of the visual environment. The best interior design schemes are a balance of variety and simplicity.
**c**. Personalization - The ability of a crewmember to personalize certain portions of her or his environment is often a morale booster. This option should be limited to an individual's personal quarters. A simple feature could be a simple bulletin board on which the crewmember could display personal photos or other memorabilia.
**d**. Maintenance of Decor - Use of a wide variety of colors, textures, materials, and accessories can exaggerate housekeeping, repair, and replacement problems.
**e.** The interior decor shall be capable of being changed with a minimum of resource expenditure.
**f.** Color Selection - The following are requirements for the use of color in the space module interior:
**1**. The use of dark (low brightness) or saturated colors shall be restricted to small areas, (e.g., handrails, display frames, etc.).
**2**. An enclosed space that is frequently occupied shall not be a uniform color throughout.
**3**. Color schemes for eating and grooming areas shall consist of colors that enhance the appearance of food and a person's skin color.
Lighting Design Considerations
Space module lighting systems should be designed to optimize viewing conditions for all mission activities. This will vary from very gross visual requirement (such as seeing to move about) to very critical visual tasks that require discrimination of color codes, seeing fine detail an instruments, or detection of dim objects or planetary detail at night.

Orientation Design Considerations
In a 1-G or partial gravity environment, orientation is not a particular problem. Down is the direction in which gravity acts and the human is normally required to work with feet down and head up. In a microgravity environment, the human working position is arbitrary. There is no gravity cue that defines up or down. In microgravity, orientation is defined primarily through visual cues which are

under the control of the system designer. The orientation within a particular crew station is referred to as a local vertical. There are several orientation factors to be considered when designing a microgravity environment.

**a**. Work Surfaces - Microgravity expands the number of possible work surfaces (walls, ceilings, as well as floors) within a given volume. This could result in a number of different local verticals within a module.

**b**. Training and Testing - Some of the working arrangements that are possible in microgravity will not easily be duplicated on Earth. Pre-mission training and testing will suffer with these arrangements. Additional training might have to be conducted during the actual mission. This could drastically reduce the effectiveness of a short duration mission.

**c**. Disorientation - Humans, raised in a 1-G environment, are accustomed to forming a mental image of their environment with a consistent orientation. People locate themselves and objects according to this mental image. If the person is viewing the environment in an unusual orientation, this mental image is not supported. This can promote disorientation, space sickness, temporary loss of direction, and overall decreased performance.

**d**. Visual Orientation Cues - Visual cues are needed to help the crewmember quickly adjust his or her orientation for a more familiar view of the world. These visual cues should define some sort of horizontal or vertical reference plane (such as the edges of a CRT or window). Of the two, it appears that the horizontal cue is more effective. Further research is presently being conducted by NASA to determine additional guidelines for the design of visual orientation cues.

**e**. Equipment Operation - Due to prior training and physical characteristics of the human, some pieces of equipment are more efficiently operated in one specific orientation. Labeling must also be properly oriented to be readable. Direction of motion stereotypes exist for most controls. For instance, in the US, power is turned on when a switch is positioned up or toward the head. If equipment items, labels, and controls have different orientations within the same crew station, human errors are likely to occur.

<u>Location Coding Design Considerations</u>

This section discusses the standards for defining locations throughout a space module and or vehicle. The location coding system shall apply to all crew interface areas.

In order to be effective, it is important that a consistent coding system be established early in the space module development. The system must be incorporated into the design of space module compartments, components, control consoles, racks, and all general installations. This coding system must then be used throughout all phases of crew training and system documentation.
plan development and communication.

<u>Architectural Considerations & Habitat Aesthetics (M. Rudisill Input)</u>

Need to define work areas, public recreational areas (shared by all crew), and private areas (for sleep, private time…). Issue is how much volume for each, where to place them (adjacencies), how to clearly demarcate them in limited pressurized volume. There is limited understanding at present concerning the amounts and type of space required for multiple (probably international) crewmembers for confined long duration missions.

<u>Exercise, Leisure, and Recreation (M. Rudisill Input)</u>

Expect primary time to be devoted to work (extreme work orientation); may also use time on personal pursuits (reading, keeping diary); expect high commitment to mission and high motivation -- work is part of this; this can be maintained for rather long period, not forever; physical environment must support work areas and leisure areas (separate); with lighter workload, expect off-duty time; want to foster leisure/recreational activities that contribute to crew health; clear preference shown for "passive" recreation that can be easily accomplished within the confines of a spacecraft (movies, television, books, music, looking out the window); Reading is a favorite pastime -- should allow individual reading preferences, electronic media to support this (ship's library). Should allow all crew to do things together (but competition kept to minimum -- could cause conflict); should allow each crewmember some time to do their personal activity; computer games could also be used for eye/hand coordination maintenance; tending a garden (for research, for food, for recreation); perhaps use time for educational pursuits (but they do need time away from work); have music and news from home sent; video communications from folks at home; can't have deliveries from home.

Exercise is required for health maintenance; can also serve leisure/recreational/relaxation/stress reduction aspect if designed properly; We need to determine types of exercise that will maintain crew health over long duration, and that crew can maintain (motivation factor). requires ability to "wash up" after workout; should be related to individual crewmember's exercise preferences (for motivation); maybe acquire a skill; again, not competitive. Maybe exercise together.

Privacy & Personal Space (M. Rudisill Input)

Most habitability complaints are about physical environment; there is also the psychological aspect, of the "need for privacy and one's own space." Need for privacy may have biological purpose and evolutionary roots. Relates to personal volume, separation from other crew, control over personal space; freedom of activity, self-disclosure. Represents control of interactions with others; choosing when and how to interact, choosing what to disclose about oneself.

In the confined volume of a spacecraft, typical mechanisms for regulating privacy may be lacking or inappropriate. As mission time continues, crewmembers will experience a need to withdraw from teammates, an understandable response but one that can reduce group cohesion. Needs balance between individual privacy and "public" group.

Many external things indicate sameness (like, uniforms). "Crowding" can also cause generalized stress. Need for privacy determined by individual (and may relate to introversion/extroversion dimension) and also by culture (privacy is culturally universal, but cultures may vary in how privacy behavior is implemented); Need becomes more pronounced with longer missions in confinement; privacy may be controlled verbally, nonverbally (body language), environmentally, and culturally-based behavior. Emphasize personal identify. Give each individual a small private area. Allow personalization of private zone. Familiarize crewmembers on need for maintaining personal privacy as well as group cohesion. Allow privacy in communications with loved ones on earth and for medical purposes.

Spacecraft design should support crew privacy and personal space needs. Understand it's difficult to achieve with such restrictions on volume for "public" and "private' volumes. Need space "cultural" norms to support privacy. Confinement usually causes greater self disclosure and strong group commitment, pressure to "tolerate" a great deal for the mission, reducing crew "right to privacy."

One special aspect relates to disclosure to general public because of public nature of mission. Could be particularly offensive (perceived as unwanted intrusion by outsiders); allow crew to have great deal of control.

References

Connors, M.M. (1985) *Living aloft: Human requirements for extended spaceflight.* NASA SP-483. Moffet Field, CA: Ames Research Center.

NASA-STD-3000. *Man-Systems Integration Standards*. Houston, TX: Johnson Space Center.

Stuster, Jack (1996) *Bold endeavors: Lessons from polar and space exploration.* Annapolis, MD: Naval Institute Press.

## 24.0 Tools, restraints, vehicle interface standards and commonality (EVA/IVA) - RKF

Tools appear in many forms to aid humans with work. Besides traditional hand tools, the basic spacecraft, information devices and robotics can be considered as "tools". The overall goal is to minimize the resources devoted to this equipment. Standardization of interfaces, minimization of actuation loads, adequate access clearances and appropriate body restraints are typical tactics for accomplishing work with least overhead and best chance of success. Where ever possible, existing designs, standards and inventory should be applied to minimize costs and manifest impacts. Vehicle assembly and maintenance tasks would ideally require no tools or a very limited standard complement of tools and associated restraints (< 10). Good tool design practice includes low mass, high strength, minimal input loads/torques/cycles, ambidexterity, ease of repair/cleaning, thermally/electrically insulated handles and restraint attachment features. By limiting the quantity and complexity of tools and vehicle interfaces, training time and personnel are also kept to a minimum.

The types of aids to be considered for interior or exterior work may include :

Self Rescue (power and gas common to suit life support, elements detachable if not needed)
Incapacitated Rescue
Freeflight translation/work (MMU???)
Lighting
Cameras (normal vision, magnify, IR, UV, low light, suited crew feedback via image display or laser pointer,digital images, still and/or video images
Body restraints
Tethers (safety, equipment)
Equipment carriers (sleds, wagon, rickshaw, wheelbarrow, stands, rover trailers, etc)
Secure restraint without relying on manual transport
Hand tools (power and manual, gripping aids/wrist straps, ambidexterous features)
Batteries/Chargers
Detectors (chemical, fluids, gases, leaks)
Diagnostics (multimeter)
Geology (shallow drills, deep drills, core tubes, hammer, chisel, rake, soil scoop/trencher, sterile labeled sample bags/containers, gnomon, 10X magnifying glass/camera, stake drivers/extractors, survey lines, inclinometer, grasp/reach tool for 10-30cm and X kg objects, dust brush, magnet, chem sniffers, leatherman pliers???)
Weather and navigation aids (wind, temperature, humidity, radiation, compass, binoculars)
Recreation (golf clubs, etc)
Markers, flags, trail blaze paint, rock cairn
Walking aids/poles
Exercise equipment (hand, forearm)
ISRU devices (sandbags)
Shelters, tents and caches
Repair tools (welders, gas/fluid patches, etc)

The mass, volume and specific selection of manifested tools is dependent upon the task challenges. For future planning based upon past history, zero-G work involving extensive assembly and maintenance could require up to **1100** lbs and **30** ft3 for tools and containers. For missions primarily focused upon planetary science, plan on approximately **xx** lbs and **yy** ft3 of support equipment. Consumable fluids, gases and power are **TBD**.

The vehicle and science interfaces to be considered for interior or exterior work may include :

Handrails (cross-section, clearances, spacing, loads, color, labels, mandatory locations)
Foot restraint attachments (clearances, loads, labels, criteria for necessity)
Tether points (clearances, dimensions, loads, criteria for necessity)
Electrical and Fluid Connectors (type, sizes, labels, self alignment, clearances)
Electrical and Fluid Connectors Caps/Covers (labels, lanyards, self venting, dust/AO/UV proof)

Electrical and Fluid Lines (free length, strain relief, bend radius, stiffness, high flexibility or dual wound to cancel line memory, restraints/spacing, labels, spacing, vent before fluid line mate/demate, trip proof line runs)
Mechanical Restraints (hard dock, soft dock, alignment aids, latches, bolt heads, self locking, captive, tethered, locking pins, max and min torque limits with and without restraint, long life temporary restraints, interior/exterior velcro, contingency release, labels, etc)
Labels and location codes (colors, contrast, fonts, sizes, content, stowage containers)
Designs to avoid (zippers, lock wire, snaps, exposed external velcro)

## 25.0 Crew Information Technology and Workstations (Rudisill)

Undoubtedly, much of the crew's work on exploration missions will be conducted at workstations while using supporting "intelligent" systems, wile some crew work will be conducted with intelligent robotic assistants in situ away from a specific workstation. Extrapolating from the present state-of-the-art to the future of human exploration of space, it may be said that the human crew and artificial systems (e.g., automation, intelligent assistants, ambulatory robots) will form collaborative teams that will work together toward common exploration goals.

With collaborative, closely-coupled work activities between humans and "artificial assistants," it is important that the interaction between human and machine be efficient and effective. Therefore, consideration must be given to the issues and requirements associated with designing this human/machine interaction.

Workstations are "collections" of multiple components that, through proper design, form an integrated, supporting environment for the work activities to be carried out. Workstation components fall into three broad categories:

- Hardware: the actual workstation structure, physical components (e.g., display monitors, control devices), and their arrangement;
- Software: providing the functionality for crew tasks and the crew information interface; and
- Information technology (IT): that provides automated and intelligent support to the human user.

The following identifies a number of high-level design guidelines and requirements for crew workstation hardware and software components, the crew/computer interface, and IT (including automation, intelligent systems, and robotics). Detailed workstation design guidance is provided in NASA-STD-3000 Man-Systems Integration Standards, Section 9.0.

It should be noted that the primary issue is the design of human interaction with work-related components and systems. All design of a human/machine system must be *human-centered*. That is, all components (including those with "intelligence") to be used by the crew should be designed as tools to be efficiently and effectively used by the crew (this does not preclude intelligent systems from some level of autonomous behavior) and interaction methods must foster easy and effective collaboration. The primary focus of workstation design should be on providing a work-space, tools, and assistance that enables the human operator and machine to perform work activities in the most effective, efficient manner. The goal is to design an *effective crew/machine system*.

Workstations

- Crew tasks must be effectively allocated to crew and machine and this allocation should guide design. Group common subtasks (with related information). Use task analysis to aid in task definition and allocation.
- Make workstations modular (e.g., having interchangeable components) and reconfigurable.
- Provide a common, standard workstation crew interface to the greatest extent practical.

Architecture

- Workstation illumination (fixed and portable/supplementary) should be consistent with crew task requirements, be adjustable, uniformly cover the entire work area (with no reflections), and be designed for light and dark adaptation state, as required by crew tasks.
- Workstation architectural configurations should consider operator task needs and capabilities, including physical dimensions, viewing angles, and distances.
- Ventilation should be consistent with NHB 8060.1; flow rate and direction should be adjustable.
- Design workstations with a specific orientation that is consistent with the orientation established within the surrounding area.
- Locate workstations to minimize interference and distractions.
- Use neutral colors that reduce reflections and provide good contrast.
- Workstation restraints (including foot and waist restraints, tethers, and handholds) should be adjustable, comfortable, and easy to engage/disengage, should provide stability, and should be compatible with task performance. Consider the neutral body posture when designing crew restraints.
- Workstations should accommodate crewmembers operating with the neutral body posture of microgravity. The design should minimize musculoskeletal tension required to maintain position, should minimize excessive movement, and should define the workstation visual space by the 0-g line of sight.
- Design workstations to accommodate the physical dimensions of a TBD user population (including restraints).
- Design specialized window workstations to support the special tasks requiring out-the-window viewing. Design window optical properties to support the requirements of crew tasks (including color discriminations); provide proper illumination (including dimming controls to allow dark adaptation) and minimize reflections. Include sunlight shielding and radiation protection. Design windows to provide orientation cues. Make windows large enough to accommodate multiple crewmembers. Include crew restraints (for up to four hours of comfortable viewing).
- Specialized maintenance workstations should provide the primary controlled-environment (e.g., conditioned/converted power, data, power, video) location for servicing and repairing components. They should provide crew access to computers displaying maintenance-related data (e.g., procedures, diagnostics, schedules), access to real-time voice and data communications, and interfaces with failure detection, fault isolation, and built-in-test capability. Restraints should be provided for positioning and restraining supporting documentation (e.g., hardcopy procedures) and should consider such crew factors as lighting, neutral body posture, and eye distance. Consideration should be given to providing “no hands” input/output capability (e.g., voice).
- “Portable workstations” should provide crew access to computer-based task support throughout pressurized volumes in addition to fixed workstations. Network-based interfaces should be provided in multiple places throughout the vehicle and in all areas where crew can go.
- Provide labels, legends, markings, codes, or a combination of these where it is necessary for a crewmember to identify, interpret, follow procedures, or avoid hazards. Use brightness, size, pattern, location, shape, text symbol (e.g., bold face, italics), flash, and color coding.

**Controls**
The following control design requirements are for ungloved operations. Advantages and disadvantages of different controls and detailed design guidance for multiple types of hardware controls (e.g., switches, toggles, levers, pushbuttons, pedals, circuit breakers, slides, legends) are given in NASA-STD-3000. Advantages and disadvantages of different computer input devices and detailed design guidance for multiple types of these devices (e.g., keyboard, joysticks, lightpen, mouse, trackball, stylus and grid, touch display, bar code reader) and guidance for the design of speech communication systems are given in NASA-STD-3000.

- Design controls to be standard across all crew/workstation interfaces.
- Design controls to accommodate accelerations within the operating environment and to withstand crew-imposed limits (across the range of the user population).
- Use control detents for discrete steps and stops at beginning and end of control range.
- Use shape coding or separation for blind operation of controls. Code and label emergency/critical controls. Do not use miniature controls.
- Protect controls from accidental actuation (by location, orientation, recessing, shielding, cover guards, interlocks, resistance, on-off, locks, or “dead-man” switch); design protection to not interfere with normal operation; protections should not occlude control position.
- For “naturalness” of communication between the human crew and machines, natural language-based voice communication (for both input and output) should be considered.

**Displays**
Displays are the primary method for providing information about systems, processes, and vehicles to the crew. Although information is primarily conveyed to the crew visually (via meters, indicators, signals, flags, and graphics-capable monitors), displays can also be auditory. A particular concern is the display of crew caution and warning information. Following is top level guidance for display design; detailed design guidance for visual displays, auditory displays, and caution and warning displays is provided in NASA-STD-3000, Section 9.4 Displays.

- Display only information required by the crewmember to perform the task; do not make displayed information over-complex; provide a simple, direct means to access more detailed information.
- Prioritize displayed information by the operator’s tasks, such that needed information is most readily available. Ensure the accuracy and range of displayed information.
- Place display surfaces to enhance readability; consider such factors as height, orientation, viewing distance, glare and reflectance, surround luminance (including other displays), controls (e.g., brightness, contrast, ambient illumination, vibration and acceleration state, and symbology type and size. Consider the operator’s dark adaptation state. Provide positive indication of the display state.
- Consider the special design requirements associated with large screens, legends, scales and pointers, clocks and timers, “flags,” digital displays, LEDs, and graphics monitors.
- Design display hardware for easy maintenance by a crew in microgravity for the long durations associated with an exploration mission (e.g., limited spares).
- Choose audio displays having optimal signal characteristics for the operating environment; design speech systems with maximum intelligibility. Consider using audio controls when hands-free operation is required.
- Display caution and warning information to warn personnel of impending danger, to alert an operator to a critical change in system or equipment status, to remind the operator of a critical action or actions that must be taken, and to provide advisory and tutorial information. Provide both visual and auditory information. Ensure that the alarm source is easily determined. Allow the crew to view alarm history. Provide a “master” alarm.
- Design the Caution and Warning System (CWS) to follow the standard alarm classification:
    - Class 1 (emergency): A life threatening condition requiring an immediate and predefined action to protect the crew.

- Class 2 (warning): Conditions requiring immediate correction to avoid loss of major impact to the mission or potential loss of crew.
- Class 3 (caution): Conditions of a less time critical nature, but with the potential for further degradation if crew attention is not given.

- When designing the CWS, consider the alarm's frequency, intensity, alerting capability, and discriminability. Design verbal alarms (i.e., speech-based) for maximal intelligibility, considering speech characteristics, intensity, message content, and repetition.
- Allow rapid CWS recovery with return to default configuration and alarm signal reset; ensure that the CWS remains operational during failures (e.g., power).
- "Advisory displays" are system-initiated messages advising of a process status or other discrete event (e.g., parameter limit). Provide a message with alerts and allow the crew to review alert history.
- "Tutorial displays" are messages denoting illegal keyboard syntax or for assisting in proper completion of required inputs. Limit tutorial displays to the local workstation.

**Display/Control Integration**

- Spacing and positioning of workstation physical controls should follow the guidance provided in MSIS NASA-STD-3000. All controls should be operable by a pressure-suited crewmember.
- Locate displays to aid the user in performing the task. Displays should be visually accessible, be properly oriented (perpendicular to the operator's line of sight), reduce parallax, support simultaneous use with controls, and provide positive and unambiguous indication of system state.
- Group functionally-related displays and controls; provide clear and readable labels; provide a common interface across functionally similar displays and controls (do not use mirror images). Arrange controls by sequence of use or by logical flow. Place the most frequently used displays and controls in optimal positions (and consider acceleration forces on crew).
- Controls and displays for maintenance tasks should not be visible during normal operations but should be readily accessible during maintenance.
- Locate emergency displays and controls to be easily seen and easily reached. Make emergency information on displays to be conspicuous and easily seen.
- Movement of controls should be consistent with associated displays. If controls have multiple uses, their movement should be consistent across their usage. Control movements should not exceed a crewmember's motor control ability in microgravity (e.g., dexterity, force).

**User/Computer Interaction**

- Aid the user in performing work by providing the required information in an appropriate format and providing well-designed interaction methods. For example, provide visual consistency across screens; give rapid and predictable feedback for all user actions; design intuitive (i.e., easy-to-learn, easy-to-use) actions or commands that do not require significant memorization; allow escape, cancel, and abort functions for all user actions; make error recovery easy; provide all information the user requires to perform the task; do not display extraneous information but allow easy and direct access to more detailed information; make consequences of user actions across displays consistent; and provide distinctive and meaningful abbreviations and acronyms.
- Analyze crew tasks to determine the information required by the crew and reflect this in displays; do not require reference to additional information sources. Prototype displays and allow operators to review them and provide feedback. Design the interaction so that the crewmember can concentrate on the task at hand, not the system. Provide information in the most appropriate format.
- Design user/computer dialogues using the method most appropriate for the task (e.g., commands, function keys, voice, menus, direct manipulation, forms, speech, macros) or provide multiple user-selectable dialogue methods. Prevent accidental actuation of potentially destructive control actions.

- Provide clear methods for users to directly interact with information in the display screen (e.g., to indicate their focus in the information display with a cursor or pointer), including manipulative actions such as scrolling, paging, hyperlinks, gross and precise positioning, selecting, cutting/pasting. Allow users to create, save, retrieve, and edit multiple types of files. While multitasking, clearly indicate the “active” screen, cursor, or area.
- Provide useful “user guidance” by using consistent terminology, feedback, error handling, and prompts, as necessary; aid the user in data error (e.g., providing the correct format; validating input values).

**Information Technology**

Information technology (IT) is a broad domain, encompassing multiple areas, such as robotics, automation, vehicle health management, human-centered computing, and intelligent systems. Unquestionably, it is expected that an exploration crew would regularly come into contact with IT-based systems, and much of their exploration work would be conducted with such technologies. As an infrastructure technology, IT enables other technologies, capabilities, and functionality for exploration missions and has the potential to increase safety, efficiency, and performance while decreasing cost. But these benefits will only be accrued to the extent to which advanced IT-based systems are designed to work collaboratively and effectively with their human team members.

There are a number of potential IT application areas within human exploration and it is to be expected that all crew activities would be highly integrated with the IT and would benefit from this collaboration. Throughout the following categories, the primary human issue is crew interaction with the IT; given the added intelligence, capability, and autonomy afforded advanced IT systems, it is even more relevant that the human/ technology interface be seamless and well designed.

Broadly defined, the categories of IT are:

(1) Automated or Robotic Assembly

IT will enable the construction of structures, such as transit vehicles, habitats, and observatories, in the zero-g environment or on a planetary surface. The human crew would be involved with such construction operations at a low level (e.g., via teleoperation of robotic manipulators) or at a high level (e.g., by commands to an autonomous system).

(2) Autonomous Science

Science provides the primary underlying purpose for exploration and much of the science will be conducted autonomously (given the distances and communications involved). Humans and IT systems may forge “collaborative” teams, with autonomous intelligent systems extending the crew’s reach and visibility. With advanced IT-based systems, the level of scientist/system interaction will change, with the crew providing high-level direction and the automated systems making basic decisions, planning, executing the plan, and carrying out much of the data collection and analysis. The primary issues involve designing effective human/system interaction and communication.

(3) Automated Operations

IT will enable the automated control of complex systems that support the human crew, such as ECLSS and ISRU production, without regular direct human control, with future IT expanding the capabilities of existing industrial automation and process control. Such automation will make complex decisions with limited or no human interaction, perhaps operating for long periods of time locally (e.g., on the Mars surface) with little or no direction from the crew or Earth-based mission controllers. In addition, the human role shifts from a direct process controller to a supervisor.

(4) Human Amplification

Fundamental human capabilities of the crew will be "amplified" or enhanced through IT. For example, in present advanced aircraft, automated flight control systems enhance the pilot's manual control of the vehicle; this capability could be extended to such areas as hazard identification and avoidance. IT systems may be used to amplify human design capabilities with collaborative design tools. Finally, IT may amplify human physical (e.g., strength) and sensory (e.g., extended vision, enhanced touch) capabilities.

(5) Vehicle Health Management (VHM)

Automated Vehicle Health Management systems monitor and manage the health and safety of the vehicle, including system monitoring, fault isolation, diagnosis, and recovery. Such IT systems would be integrated into multiple vehicles (and potentially into structures such as the habitat on the planetary surface). Advanced VHM systems have intelligence, enabling fundamental decision making and authority to effect changes in vehicle physical state.

Many of the issues surrounding human interaction and cooperation with advanced IT-based systems stem from their intelligent and autonomous nature. Present IT-based systems typically require direct human control and pre-programmed behavior, setting strong boundaries on missions and expectations with regard to artificial systems. In future exploration missions, these IT-based devices will operate more like automated assistants or team members. Therefore, systems must behave effectively and appropriately within a framework of significant communication delays, high complexity, harsh operating environments, and little or no human direction. Some of the characteristics of advanced IT devices for exploration missions that must be considered when developing human/IT systems are:

(1) High autonomy and capability to make critical decisions independent of human operators.
(2) Robustness, ability to respond effectively to uncertainty and unknown environments over long durations (where degradation or failure is likely).
(4) Environmental and situational adaptability.
(5) Biologically-inspired low-level adaptive control and reflexive responses.
(6) Architectures with an executive, responsible for selecting actions based on sensory information, and health management, responsible for monitoring the state of the system in real-time.
(7) Flexible planning and scheduling functions, for reasoning about high-level goals and defining actions to satisfy the goals, used within a closed-loop to control the autonomous system.
(8) Distributed decision-making between independent cooperating autonomous agents, including shared resources and coordinated roles, such as within a "robotic colony" on a planetary surface or a fleet of sensing devices.

Again, the primary issue with regard to humans is the ability to interact and cooperate with advanced IT systems to conduct the mission, in a safe, effective, efficient manner. Intelligent systems must be designed to facilitate human/system interaction and cooperation; they must be designed following human-centered principles.

References:
**2001, Hine, Butler & Clancy, Dan. "The Role of Information Technology in Human Space Exploration"; NASA ARC.**

EVA Factors (RKF)

EVA unique interfaces should consider additional environmental and human factors constraints. For externally mounted displays, bright solar lighting, vacuum pressures and extreme hot/cold temperatures must be addressed. Rather than rely on fatiguing and imprecise gloved finger controls, hands free alternatives are necessary (e.g. voice actuation, eye tracking or whole arm/hand tracking). If interfaces internal to the suit are devised, they must be safe for 100% O2 atmosphere and very small to fit within the extremely limited free volume of the garment/helmet.

## 26.0 Crew Accommodations (Stilwell)

Crew accommodations are those elements of mission hardware, software, and even procedures that most directly serve the needs of the crewmembers. The factors and calculations used here are taken directly from the resource model described in Chapter 18, "Crew Accommodations," in Human Spaceflight Mission Analysis and Design. Stilwell, D., Boutros, R., and J. Connolly. New York: McGraw Hill Companies, 1999.

Before using this model, please consider the following caveats (paraphrased from Chapter 18):

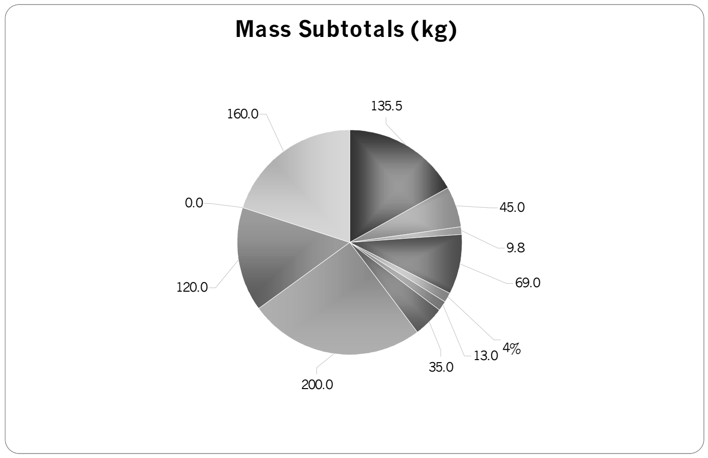
1. This resource model considers system-level components but does exclude several common components of habitat architecture and life support:
   - **potable and hygiene water**, because the quantity needed depends on the onboard reserves and reclamation system employed
   - **integration hardware** needed to install/attached crew accommodations, such as lockers or racks
   - **resources for spare or replacement parts**, because the quantities needed are based on system reliabilities
   - **contingency supplies**, because the quantities needed require separate analysis of potential mission failures.
2. The suggested mass and volume factors used in this resource model are just that: educated guesses and estimates based on historical data (to some extent) and on the assumption that new technologies with efficient design will be used.
3. Mass and volume factors are given for four mission types: Shuttle (short-duration Earth orbit), Station (long-duration Earth orbit), lunar base (medium-duration surface activities), and Mars habitation (long-duration surface habitation). These types are not based on current systems or programs but are intended to represent typical mission objectives.

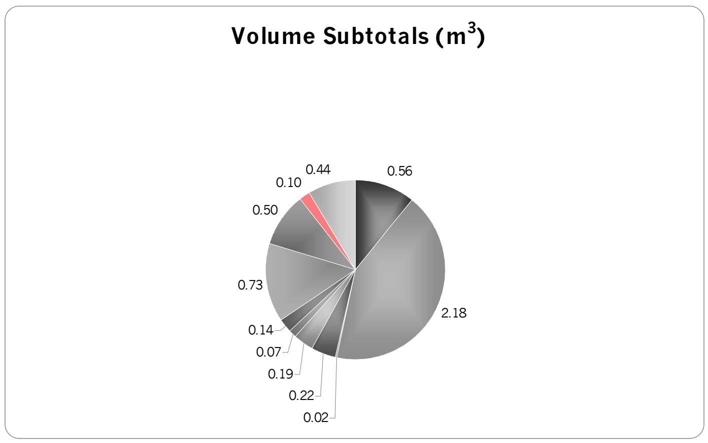
This file consists of several spreadsheets that together permit you to make basic calculations and comparisons of crew accommodations for different mission scenarios:

1. **Mass Factors**: this table lists mass factors of 11 crew accommodations systems for the four mission types.
2. **Volume Factors**: this table lists volume factors of 11 crew accommodations systems for the four mission types.
3. **Calculations**: this spreadsheet allows you to create a mission scenario by selecting mission type, crew size (1-10), and duration. The spreadsheet then automatically calculates mass and volume subtotals based on the suggested factors and your scenario choices.
4. **System Subtotals**: this spreadsheet automatically summarizes the subtotals and totals for your scenario in table and graphic (pie chart) format.

| | |
|---|---|
| Mission type: | 1 |
| Crew Size: | 1 |
| Duration (days): | 0 |

| System | Mass Subtotal (kg) | Percent Total Mass (kg) |
|---|---|---|
| Galley and Food | 135.5 | 17.0 |
| Waste Collection | 45.0 | 5.6 |
| Personal Hygiene | 9.8 | 1.2 |
| Clothing | 69.0 | 8.7 |
| Recreation | 10.0 | 1.3 |
| Housekeeping | 13.0 | 1.6 |
| Operations | 35.0 | 4.4 |
| Maintenance | 200.0 | 25.1 |
| Photography | 120.0 | 15.1 |
| Sleep Accommodations | 0.0 | 0.0 |
| Crew Health Care | 160.0 | 20.1 |
| TOTAL | 797.3 | 100.0 |




| System | Volume Subtotal (m3) | Percent Total Volume (m3) |
|---|---|---|
| Galley and Food | 0.56 | 11.0 |
| Waste Collection | 2.18 | 42.3 |
| Personal Hygiene | 0.02 | 0.3 |
| Clothing | 0.22 | 4.3 |
| Recreation | 0.19 | 3.7 |
| Housekeeping | 0.07 | 1.4 |
| Operations | 0.14 | 2.6 |
| Maintenance | 0.73 | 14.2 |
| Photography | 0.50 | 9.7 |
| Sleep Accommodations | 0.10 | 1.9 |
| Crew Health Care | 0.44 | 8.5 |
| TOTAL | 5.15 | 100.0 |

Table 18-5. Mass Factors for Crew Accommodations in Various Mission Types1

Factors given are for hypothetical Shuttle-like (14-21 d), Station-like (90 d), lunar base (180-365 d), and Mars habitation (180-700 d) missions, showing how the model might be customized for different scenarios. The notation "kg/p/d" indicates kilograms/person/day.

| Crew Accommodations System | Mass Factors | | | | | Assumptions and Notes |
|---|---|---|---|---|---|---|
| | Shuttle-like | Station-like | Lunar base | Mars hab | Units | |
| **Galley and Food System** | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Food | 2.3 | 2.3 | 2.3 | 2.3 | kg/p/d | Minimum is 1.8 kg/p/d (current Shuttle allowance) |
| Freezer(s) | | | 100 | 400 | kg | Empty freezer (no food mass included) |
| Conventional ovens | 50 | 50 | 50 | 50 | kg | |
| Microwave ovens | 70 | 70 | 70 | 70 | kg | Assumes 2 ovens |
| Cleaning supplies | 0.25 | 0.25 | 0.25 | 0.25 | kg/d | Includes solvents and supplies for cleaning galley and ovens |
| Sink and spigot | 15 | 15 | 15 | 15 | kg | For food rehydration and drinking water |
| Dishwasher | | | 40 | 40 | kg | |
| Cooking/eating supplies | 0.5 | 0.5 | 2 | 5 | kg/p | |
| **Waste Collection System** | | | | | | |
| System | 45 | 45 | 45 | 90 | kg | Assumes 1 toilet for each mission except Mars (2 toilets) |
| Supplies | 0.05 | 0.05 | 0.05 | 0.05 | kg/p/d | |
| Contingency collection mittens/bags | 0.23 | 0.23 | 0.23 | 0.23 | kg/p/d | |
| **Personal Hygiene** | | | | | | |
| Shower | 0 | 75 | 75 | 75 | kg | |
| Handwash/mouthwash faucet | 8 | 8 | 8 | 8 | kg | |
| Personal hygiene kit | 1.8 | 1.8 | 1.8 | 1.8 | kg/p | |
| Hygiene supplies | 0.075 | 0.075 | 0.075 | 0.075 | kg/p/d | Consumables |
| **Clothing**[2] | | | | | | |
| Clothing | 69 | 214 | 69 | 99 | kg/p | Assumes 2.3 kg/p for 1 complete change of clothes |
| Washing machine | 0 | 0 | 100 | 100 | kg | |
| Clothes dryer | 0 | 0 | 60 | 60 | kg | |
| **Recreational Equipment** | | | | | | |
| Personal stowage | 10 | 25 | 25 | 50 | kg/p | |
| **Housekeeping** | | | | | | |
| Vacuum | 13 | 13 | 13 | 13 | kg | Prime and 2 spares |
| Disposable wipes for housecleaning | 0.15 | 0.30 | | | kg/p/d | |
| Trash compactor/trash lock | 0 | 150 | 150 | 150 | kg | |
| Trash bags | 0.05 | 0.05 | 0.05 | 0.05 | kg/p/d | |
| **Operational Supplies and Restraints** | | | | | | |
| Operational supplies | 10 | 20 | 20 | 20 | kg/p | Includes diskettes, ziplocks, tape… |
| Restraints | 25 | 83 | 50 | 100 | kg | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Maintenance** | | | | | | Assumes all repairs in habitable areas |
| Hand tools and accessories | 100 | 200 | 200 | 300 | kg | |
| Spare parts and consumables | | | | | - | Assumes no spare parts or consumables for maintenance |
| Test equipment | 50 | 100 | 300 | 500 | kg | Includes oscilloscopes, gauges, etc. |
| Other tools and equipment | 50 | 50 | 600 | 1000 | kg | Includes fixtures, large machine tools, gloveboxes, etc. |
| **Photography** | | | | | | Assumes an all-digital approach |
| Equipment | 120 | 120 | 120 | 120 | kg | Includes still and video cameras, lenses, etc. but no film |
| **Sleep Accommodations** | | | | | | |
| Sleep provisions | 9.00 | 9.00 | 9.00 | 9.00 | kg/p | Includes sleep restraints only |
| **Crew Health Care** | | | | | | |
| Exercise equipment | 145 | 145 | 145 | 145 | kg | Assumes 2 devices for aerobic exercise |
| Medical/surgical/dental suite | 15 | 250 | 500 | 1000 | kg | |
| Medical/surgical/dental consumables | | 125 | 250 | 500 | kg | |

1From: Chapter 18, "Crew Accommodations", in Human Spaceflight Mission Analysis and Design. Stilwell, D., Boutros, R., and J. Connolly. New York: McGraw Hill Companies, 1999.

2This is an important trade to consider for long-duration mission because it involves supplying complete sets of clothes for the duration of the mission versus using a clothes cleaning system. By default, this model assumes that a washer/dryer system is not appropriate for Shuttle- or Station-like missions and that the clothing mass for lunar/Mars missions includes cleaning and reuse of clothing. Generally, the following rule of thumb applies: if the mass (washer+dryer+cleaning supplies) < mass of clothing (duration*crew size*0.46 kg/p/d), then a cleaning system should be considered to lower clothing mass. The mass factor 0.46 kg/p/d assumes 2.3 kg for 1 change of clothes and a clothing change every 5 days.

Table 18-5. Volume Factors for Crew Accommodations in Various Mission Types1

Factors given are for hypothetical Shuttle-like (14-21 d), Station-like (90 d), lunar base (180-365 d), and Mars habitation (180-700 d) missions, showing how the model might be customized for different scenarios. The notation "kg/p/d" indicates kilograms/person/day.

| Crew Accommodations System | Volume Factors | | | | | Assumptions and Notes |
|---|---|---|---|---|---|---|
| | Shuttle-like | Station-like | Lunar base | Mars hab | Units | |
| **Galley and Food System** | | | | | | |
| Food | 0.0080 | 0.0080 | 0.0080 | 0.0080 | $m^3$/p/d | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Freezer(s) | 0 | 0 | 0.50 | 2.00 | $m^3$ | |
| Conventional ovens | 0.25 | 0.25 | 0.25 | 0.25 | $m^3$ | |
| Microwave ovens | 0.30 | 0.30 | 0.30 | 0.30 | $m^3$ | Assumes 2 ovens |
| Cleaning supplies | 0.0018 | 0.0018 | 0.0018 | 0.0018 | $m^3$/d | Includes solvents and supplies for cleaning galley and ovens |
| Sink and spigot | 0.0135 | 0.0135 | 0.0135 | 0.0135 | $m^3$ | For food rehydration and drinking water |
| Dishwasher | 0 | 0 | 0.56 | 0.56 | $m^3$ | |
| Cooking/eating supplies | 0.0014 | 0.0014 | 0.0056 | 0.014 | $m^3$/p | |
| **Waste Collection System** | | | | | | |
| System | 2.18 | 2.18 | 2.15 | 4.36 | $m^3$ | Assumes 1 toilet for each mission except Mars (2 toilets) |
| Supplies | 0.0013 | 0.0013 | 0.0013 | 0.0013 | $m^3$/p/d | |
| Contingency collection mittens/bags | 0.0008 | 0.0003 | 0.0008 | 0.0008 | $m^3$/p/d | |
| **Personal Hygiene** | | | | | | |
| Shower | 0 | 1.41 | 1.41 | 1.14 | $m^3$ | |
| Handwash/mouthwash faucet | 0.01 | 0.001 | 0.01 | 0.01 | $m^3$ | |
| Personal hygiene kit | 0.005 | 0.005 | 0.005 | 0.005 | $m^3$/p | |
| Hygiene supplies | 0.0015 | 0.0015 | 0.0015 | 0.0015 | $m^3$/p/d | Consumables |
| **Clothing**[2] | | | | | | |
| Clothing | 0.224 | 0.720 | 0.224 | 0.336 | $m^3$/p | Assumes 0.008$m^3$/p for 1 complete change of clothes |
| Washing machine | 0 | 0 | 0.75 | 0.75 | $m^3$ | |
| Clothes dryer | 0 | 0 | 0.75 | 0.75 | $m^3$ | |
| **Recreational Equipment** | | | | | | |
| Personal stowage | 0.19 | 0.38 | 0.38 | 0.75 | $m^3$ | |
| **Housekeeping** | | | | | | |
| Vacuum | 0.07 | 0.07 | 0.07 | 0.07 | $m^3$ | Prime and 2 spares |
| Disposable wipes for housecleaning | 0.001 | 0.002 | 0 | 0 | $m^3$/p/d | |
| Trash compactor/trash lock | 0 | 0.3 | 0.3 | 0.3 | $m^3$ | |
| Trash bags | 0.001 | 0.001 | 0.001 | 0.001 | $m^3$/p/d | |
| **Operational Supplies** | | | | | | |
| Operational supplies | 0.001 | 0.002 | 0.002 | 0.002 | $m^3$/p | Includes diskettes, ziplocks, tape… |
| Restraints | 0.135 | 0.54 | 0.27 | 0.54 | $m^3$/kg | |
| **Maintenance** | | | | | | Assumes all repairs in habitable areas |

| | | | | | | |
|---|---|---|---|---|---|---|
| Hand tools and accessories | 0.33 | 0.66 | 0.66 | 1.00 | $m^3$ | |
| Spare parts and consumables | | | | | - | Assumes no spare parts or consumables for maintenance |
| Test equipment | 0.15 | 0.3 | 0.9 | 1.50 | $m^3$ | Includes oscilloscopes, gauges, etc. |
| Other tools and equipment | 0.25 | 0.25 | 3.00 | 5.00 | $m^3$ | Includes fixtures, large machine tools, gloveboxes, etc. |
| **Photography** | | | | | | Assumes an all-digital approach |
| Equipment | 0.50 | 0.50 | 0.50 | 0.50 | $m^3$ | Includes still and video cameras, lenses, etc. but no film |
| **Sleep Accommodations** | | | | | | Does not include recommended 1.5 $m^3$/p for sleeping |
| Sleep provisions | 0.10 | 0.10 | 0.10 | 0.10 | $m^3$/p | Includes sleep restraints only (suitable for short duration) |
| **Crew Health Care** | | | | | | |
| Exercise equipment | 0.19 | 0.19 | 0.19 | 0.19 | $m^3$ | Assumes 2 devices for aerobic exercise |
| Medical/surgical/dental suite | 0.25 | 1.00 | 2.00 | 4.00 | $m^3$ | |
| Medical/surgical/dental consumables | | 0.64 | 1.30 | 2.50 | $m^3$ | |

1From: Chapter 18, "Crew Accommodations", in Human Spaceflight Mission Analysis and Design. Stilwell, D., Boutros, R., and J. Connolly. New York: McGraw Hill Companies, 1999.

2This is an important trade to consider for long-duration mission because it involves supplying complete sets of clothes for the duration of the mission versus using a clothes cleaning system. By default, this model assumes that a washer/dryer system is not appropriate for Shuttle- or Station-like missions and that the clothing volume for lunar/Mars missions includes a cleaning system and reuse of clothing.
Generally, the volume factor assumes 0.008 m3/p for 1 change of clothes and a clothing change every 5 days.

Mass and Volume Calculations by Mission Type, Crew Size, and Duration1

*Mission Type:* Shuttle-like

*Crew Size:* 1

*Duration (days):*

| Crew Accommodations System | Mass Factor (see sheet 2) | Mass Subtotal (kg) | Volume Factor (see sheet 3) | Volume Subtotal ($m^3$) |
|---|---|---|---|---|
| **Galley and Food** | | 135.5 | | 0.565 |
| Food | 2.3 kg/p/d | 0.0 | 0.008 $m^3$/p/d | 0.000 |

| | | | | | |
|---|---|---|---|---|---|
| Freezer(s) | 0 | kg | 0 | 0.000 $m^3$ | 0.000 |
| Conventional ovens | 50 | kg | 50 | 0.250 $m^3$ | 0.250 |
| Microwave ovens | 70 | kg | 70 | 0.300 $m^3$ | 0.300 |
| Cleaning supplies | 0.25 | kg/d | 0.00 | 0.002 $m^3$/d | 0.000 |
| Sink and spigot | 15 | kg | 15 | 0.014 $m^3$ | 0.014 |
| Dishwasher | 0 | kg | 0 | 0 $m^3$ | 0 |
| Cooking/eating supplies | 0.5 | kg/p | 1 | 0.001 $m^3$/p | 0.001 |
| **Waste Collection** | | | **45.0** | | **2.180** |
| System | 45 | kg | 45 | 2.180 $m^3$ | 2.180 |
| Supplies | 0.05 | kg/p/d | 0.00 | 0.001 $m^3$/p/d | 0.000 |
| Contingency collection mittens/bags | 0.23 | kg/p/d | 0 | 0.001 $m^3$/p/d | 0.000 |
| **Personal Hygiene** | | | **9.8** | | **0.015** |
| Shower | 0 | kg | 0 | 0.000 $m^3$ | 0.000 |
| Handwash/mouthwash faucet | 8 | kg | 8 | 0.010 $m^3$ | 0.010 |
| Personal hygiene kit | 1.8 | kg/p | 1.8 | 0.005 $m^3$/p | 0.005 |
| Hygiene consumables | 0.08 | kg/p/d | 0.0 | 0.002 $m^3$/p/d | 0.000 |
| **Clothing** (review notes in factors sheets to determine trades) | | | **69** | | **0.224** |
| Clothing | 69 | kg/p | 69 | 0.224 $m^3$/p | 0.224 |
| Washing machine | 0 | kg | 0 | 0 $m^3$ | 0 |
| Clothes dryer | 0 | kg | 0 | 0 $m^3$ | 0 |
| **Recreational Equipment** | | | **10** | | **0.190** |
| Personal stowage | 10 | kg/p | 10 | 0.190 $m^3$ | 0.190 |
| **Housekeeping** | | | **13.0** | | **0.070** |
| Vacuum | 13 | kg | 13 | 0.070 $m^3$ | 0.070 |
| Disposable wipes for housecleaning | 0.15 | kg/p/d | 0 | 0.001 $m^3$/p/d | 0.000 |
| Trash compactor/trash lock | 0 | kg | 0 | 0.000 $m^3$ | 0.000 |
| Trash bags | 0.05 | kg/p/d | 0.00 | 0.001 $m^3$/p/d | 0.000 |
| **Operational Supplies and Restraints** | | | **35** | | **0.136** |
| Operational supplies | 10 | kg/p | 10 | 0.001 $m^3$/p | 0.001 |
| Restraints | 25 | kg | 25 | 0.135 $m^3$/kg | 0.135 |
| **Maintenance** | | | **200** | | **0.730** |
| Hand tools and accessories | 100 | kg | 100 | 0.330 $m^3$ | 0.330 |
| Spare parts and consumables | - | | 0 | - $m^3$ | 0 |
| Test equipment | 50 | kg | 50 | 0.150 $m^3$ | 0.150 |

| System | Mass Subtotal (kg) | Percent Total Mass (kg) |
|---|---|---|
| Galley and Food | 135.5 | 17.0 |
| Waste Collection | 45.0 | 5.6 |
| Personal Hygiene | 9.8 | 1.2 |
| Clothing | 69.0 | 8.7 |
| Recreation | 10.0 | 1.3 |
| Housekeeping | 13.0 | 1.6 |
| Operations | 35.0 | 4.4 |
| Maintenance | 200.0 | 25.1 |
| Photography | 120.0 | 15.1 |
| Sleep Accommodations | 0.0 | 0.0 |
| Crew Health Care | 160.0 | 20.1 |
| TOTAL | 797.3 | 100.0 |

| | | | | |
|---|---|---|---|---|
| Fixtures, large machine tools, gloveboxes, etc. | 50 kg | 50 | 0.250 $m^3$ | 0.250 |
| **Photography** | | **120** | | **0.500** |
| Equipment | 120 kg | 120 | 0.500 $m^3$ | 0.500 |
| **Sleep Accommodations** | | **0** | | **0.100** |
| Sleep provisions | 9 kg/p | 0 | 0.100 $m^3$/p | 0.100 |
| **Crew Health Care** | | **160** | | **0.440** |
| Exercise equipment | 145 kg | 145 | 0.190 $m^3$ | 0.190 |
| Medical/surgical/dental suite | 15 kg | 15 | 0.250 $m^3$ | 0.250 |
| Medical/surgical/dental consumables | 0 kg | 0 | 0.000 $m^3$ | 0.000 |
| | TOTAL (kg) | 797.3 | TOTAL ($m^3$) | 5.15 |

| | |
|---|---|
| Mission type: | 1 |
| Crew Size: | 1 |
| Duration (days): | 0 |

| System | Volume Subtotal (m3) | Percent Total Volume (m3) |
|---|---|---|
| Galley and Food | 0.56 | 11.0 |
| Waste Collection | 2.18 | 42.3 |
| Personal Hygiene | 0.02 | 0.3 |
| Clothing | 0.22 | 4.3 |
| Recreation | 0.19 | 3.7 |
| Housekeeping | 0.07 | 1.4 |
| Operations | 0.14 | 2.6 |
| Maintenance | 0.73 | 14.2 |
| Photography | 0.50 | 9.7 |
| Sleep Accommodations | 0.10 | 1.9 |
| Crew Health Care | 0.44 | 8.5 |
| TOTAL | 5.15 | 100.0 |

Crew accommodations, in the broadest sense, are those elements of mission hardware and software, even procedures, that most directly serve human needs

- Galley, food system and wardroom
- Sleep accommodations and crew quarters
- Personal hygiene and toilet
- Clothing system
- Crew health care
- Emergency provisions
- Recreation hardware
- Maintenance
- Housekeeping and trash
- Photographic equipment
- Restraints and Mobility Aids (R & MAs)

<u>Crew Accommodations Mass and Volume Resource Model</u>
The example shown is a 6 crew, 500 day Mars surface stay  The model should not be slavishly applied, but should be modified to tailor it to the specific mission application.  If a particular element does not apply to a particular mission, it should be allocated zero resources in the model

| | MASS | SUBTOT (kg) | VOLUME | SUBTOT ($m^3$) |
|---|---|---|---|---|
| **Galley and Food System** | | | | |
| Food | 2.3 kg/person/day | 6900 | 0.0075 $m^3$/person/day | 22.50 |
| Freezers | 400 kg (empty) | 400 | 2.00 $m^3$ (less food vol | 2.00 |
| Conventional Oven | 50 kg | 50 | 0.09 $m^3$ | 0.09 |
| Microwave Ovens (2 ea) | 70 kg | 70 | 0.30 $m^3$ | 0.30 |
| Kitchen/Oven Cleaning Supplies (fluids, sponges, etc) | 0.25 kg/day | 125 | 0.0006 $m^3$/day | 0.30 |
| Sink, Spigot for Hydration of food & drinking water | 15 kg | 15 | 0.0135 $m^3$ | 0.01 |
| Dishwasher | 40 kg | 40 | 0.15 $m^3$ | 0.15 |
| Cooking/Eating Supplies (pans, plastic dishes, plates,etc.) | 5 kg/person | 30 | 0.014 $m^3$/person | 0.08 |
| **Waste Collection System** | | | | |
| Waste Collection System (2 toilets) | 90 kg | 90 | 4.36 $m^3$ for both | 4.36 |
| WCS Supplies (toilet paper, cleaning solutions, filters, etc) | 0.15 kg/person/day | 450 | 0.0018 $m^3$/person/day | 5.40 |
| Contingency fecal and urine collection mittens/bags | 0.23 kg/person/day | 690 | 0.0008 $m^3$/person/day | 2.40 |
| **Personal Hygiene** | | | | |
| Shower | 75 kg | 75 | 1.41 $m^3$ | 1.41 |
| Handwash/mouthwash faucet | 8 kg | 8 | 0.01 $m^3$ | 0.01 |
| Personal Hygiene Kit | 1.8 kg/person | | | |
| Hygiene Supplies | 0.3 kg/person/day | 900 | 0.002 $m^3$/person/day | 6.00 |
| **Clothing** | | | | |
| Clothing | 99 kg/person | 594 | 0.336 $m^3$/person | 2.02 |
| Washing Machine | 100 kg | 100 | 0.15 $m^3$ | 0.15 |
| Clothes Dryer | 60 kg | 60 | 0.20 $m^3$ | 0.20 |
| **Recreational Equipment & Personal Stowage** | | | | |
| Personal Stowage/closet space | 50 kg/person | 300 | 0.75 $m^3$ | 4.50 |
| **Housekeeping** | | | | |
| Vacuum Bags | 0.02 kg/day | 10 | 0.00002 $m^3$/day | 0.01 |
| Vacuum (Prime + 2 spares) | 13 kg | 13 | 0.07 $m^3$ | 0.07 |
| Disposable Wipes for housecleaning | 0.3 kg/person/day | 900 | 0.002 $m^3$/person/day | 6 |
| Trash Compactor/Trash Lock | 150 kg | 150 | 0.15 $m^3$ | 0.15 |
| Trash Bags | 0.1 kg/person/day | 300 | 0.0001 $m^3$/person/day | 0.30 |
| **Operational Supplies & Restraints** | | | | |
| Operational Supplies(diskettes, ziplocks, velcro, tape .... | 20 kg/person | 120 | 0.002 $m^3$/person | 0.24 |
| Restraints & Mobility Aids | 100 kg | 100 | 0.54 $m^3$/kg | 0.54 |
| **Maintenance:all repairs in habitable areas** | | | | |
| Hand Tools and accessories | 300 kg | 300 | 1.00 $m^3$ | 1.00 |
| Spare Parts/Equip and Consummables | -- | -- | -- | -- |
| Test Equipment (Oscilloscopes, Gauges, etc.) | 500 kg | 500 | 1.50 $m^3$ | 1.50 |
| Fixtures, Large Machine Tools, Gloveboxes, etc. | 1000 kg | 1000 | 3.00 $m^3$ | 3.00 |
| **Photography** | | | | |
| Equipment (still & video cameras, lenses, etc.) | 120 kg | 120 | 0.30 $m^3$ | 0.30 |
| Film (Assumes All Digital Approach) | 0 kg | 0 | 0.00 $m^3$ | 0.00 |
| **Sleep Accommodations** | | | | |
| Sleep Provisions | 9 kg/person | 54 | 0.10 $m^3$/person | 0.60 |
| **Crew Health Care** | | | | |
| Exercise Equipment | 145 kg | 145 | 0.19 $m^3$ | 0.19 |
| Medical/Surgical/Dental Suite | 1000 kg | 1000 | 2.50 $m^3$ | 2.50 |
| Medical/Surgical/Dental Consummables | 500 kg | 500 | 1.25 $m^3$ | 1.25 |
| | TOTAL (kg) | **16109.0** | TOTAL ($m^3$) | **69.52** |

Galley, Food System, and Wardroom

Personal hygiene

– Wet wipes are sufficient for whole body cleansing during short duration missions such as the Shuttle

– Showers are a must for long flights

»The Russian MIR shower has a water-tight, rigid wall that surrounds the user and prevents water from leaking into the rest of the cabin

•Cosmonauts are allowed 10 liters per shower which are then returned to the water reclamation system for water extraction and reuse

»Skylab had a soft-walled, collapsible shower that earned a reputation for being so difficult to use and clean that it was rarely used

»A rigid-walled shower is better choice for a long duration mission

Clothing

– The standard is 2.3 kg/person/day and 0.008 $m^3$ (69 kg for 90 days)

– The trade to a washer/dryer is made when the total clothing mass exceeds that of washer/dryer plus consumables

Crew Health System (CHS): Medical Care, Health Maintenance, and Environmental Monitoring

–Serves three major purposes

(1) Medical diagnosis and treatment of sick crew members

(2) Maintenance of optimal health in well crew

(3) Environmental monitoring to warn the crew of exposures to medical hazards, such as ionizing radiation or harmful chemicals in the air or water

–Mass and volume

»ISS estimates are 460 kg and 1.7 $m^3$ of which 260 kg and 1.1 $m^3$ are consumables

»To Mars, estimates per habitable vehicle are at least 1,000 kg for equipment and 500 kg for consumables, with a total volume of 4 $m^3$

Exercise Equipment

–Exercise equipment is an important addition to all but the shortest flights to provide exercise countermeasures for maintaining physiological health

–The Shuttle Treadmill with all of its associated supplies and fixtures has a mass of about 106 kg and a volume of 0.1 $m^3$ stowed

–The Shuttle Rowing Machine has a mass of about 34 kg and stowed volume of about 0.04 $m^3$

Emergency Provisions

–For example, the Space Station will carry fifteen Portable Breathing Kits, each consisting of a mask, a hose, and a canister of compressed gas

»Each intended to sustain an astronaut during a depressurization or toxic release with a mass of about 40 kg and a volume of 0.19 $m^3$

Recreation Hardware

–Questionnaire responses of 30 astronauts as well as Skylab and Shuttle crew reports identify looking out the window as the most favored recreational activity, followed closely by listening to tapes or CDs, physical exercise, reading, real-time communication with family, and watching television

–For a long mission with 3-6 crew, we might assume 50 kg for books and 50 kg for Audio, Video, and Data CDs

Crew Compartment Maintenance System

–38 kg and 0.2 $m^3$ volume is a reasonable estimate for a 30-day tool kit in a Shuttle-like vehicle

»Basic hand tools and supplies, including small quantities of wire, tape, hoses and a few other quick patch items

–ISS will carry a maintenance tool kit estimated at 145 kg and 0.45 $m^3$ for durable hardware with an additional 18.2 kg and 0.14 $m^3$ reserved for consumables

–For a Mars Maintenance System, estimate 580 kg/1.8 $m^3$ for durables and 182 kg/1.4 $m^3$ for consumables

Housekeeping and Trash Management

–To estimate the total number of wipes for the Space Station Habitation and Laboratory Modules, designers assume that each astronaut will use 3 utensil detergent wipes, 3 utensil rinse wipes, 4 detergent wipes, 1 disinfectant and 8 dry wipes for housekeeping activities on an average day--about 0.15 kg/person/day and a volume of 0.001 $m^3$/person/day

–For long duration missions double this to 0.3 kg/person/day and 0.002 $m^3$/person/day

–For LEO missions, trash must be compacted and returned to Earth

–For Mars or Moon intransit missions, trash could be expelled into space through an airlock as was done on Skylab

Restraint and Mobility Aids

–The U.S. Laboratory and Habitation Modules in the International Space Station will be outfitted with 83 kg of restraints and mobility aids (R&MAs), not including the sleep restraints

»When stowed, they will consume about 0.54 $m^3$

»These include long and short duration foot restraints, handrails, aisle mounted equipment anchors, tethers, etc.

Photographic Equipment

–Video, movies, and photographs transmitted or returned to Earth are the public's most obvious return on their investment in the space program

»The first Mars explorers will probably carry a high-speed, high resolution motion picture camera like the IMAX

»Because of the need to broadcast current video of the highest quality, future Mars explorers will carry digital video cameras with the same speed and quality as current high-speed, high-resolution, large-format cameras

»The ISS will use photographic equipment for scientific, engineering, and documentary activities

•The ISS photographic equipment includes several commercial-off-the-shelf (COTS) items such as a 16 mm motion picture camera and 35 and 70 mm still cameras, a 5" still camera for Earth observation, and a variety of lenses, accessories and supplies for each

•The estimated power consumption is 150 Watt-hrs/day

Tailoring the Model for Shuttle, Station, Moon & Mars

Crew Accommodations mass and volume factors are given for hypothetical Shuttle, Station, Mars Base and Lunar Base, showing how the model might be customized for different applications. It is unnecessary to show power consumption and duty cycles as the former may be scaled by a mass fraction multiplier and the latter should be relatively constant

| | MASS (kg) | | | | | VOLUME (m3) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mars Base | Lunar Base | Shuttle -like | Station -like | | Mars Base | Lunar Base | Shuttle -like | Station -like | |
| **Galley and Food System** | | | | | | | | | | |
| Food | 2.3 | 2.3 | 2.3 | 2.3 | kg/person/day | 0.0075 | 0.0075 | 0.0075 | 0.0075 | $m^3$/person/day |
| Freezers | 400 | 100 | 0 | 0 | kg (empty) | 2.00 | 0.50 | 0 | 0 | $m^3$ (less food vol |
| Conventional Ovens (3ea+spare parts) | 50 | 50 | 50 | 50 | kg | 0.09 | 0.09 | 0.09 | 0.09 | $m^3$ |
| Microwave Ovens (3ea+spare parts) | 70 | 70 | 70 | 70 | kg | 0.30 | 0.30 | 0.30 | 0.30 | $m^3$ |
| Kitchen/Oven Cleaning Supplies (fluids, sponges, etc) | 0.25 | 0.25 | 0.25 | 0.25 | kg/day | 0.006 | 0.010 | 0.010 | 0.010 | $m^3$/day |
| Sink, Spigot for Hydration of food & drinking water | 15 | 15 | 15 | 15 | kg | 0.0135 | 0.0135 | 0.0135 | 0.0135 | $m^3$ |
| Dishwasher | 40 | 40 | 0 | 0 | kg | 0.15 | 0.15 | 0 | 0 | $m^3$ |
| Cooking/Eating Supplies (pans, plastic dishes, plates,etc.) | 5 | 2 | 0.5 | 0.5 | kg/person | 0.014 | 0.0056 | 0.0014 | 0.0014 | $m^3$/person |
| **Waste Collection System** | | | | | | | | | | |
| Waste Collection System | 90 | 45 | 45 | 45 | kg | 4.36 | 2.18 | 2.18 | 2.18 | $m^3$ for both |
| WCS Supplies (toilet paper, cleaning solutions, filters, etc) | 0.15 | 0.15 | 0.15 | 0.15 | kg/person/day | 0.0018 | 0.0018 | 0.0018 | 0.0018 | $m^3$/person/day |
| Contingency fecal and urine collection mittens/bags | 0.23 | 0.23 | 0.23 | 0.23 | kg/person/day | 0.0008 | 0.0008 | 0.0008 | 0.0008 | $m^3$/person/day |
| **Personal Hygeine** | | | | | | | | | | |
| Shower | 75 | 75 | 0 | 75 | kg | 1.41 | 1.41 | 0 | 1.41 | $m^3$ |
| Handwash/mouthwash faucet | 8 | 8 | 8 | 8 | kg | 0.01 | 0.01 | 0.01 | 0.01 | $m^3$ |
| Personal Hygiene Kit | 1.8 | 1.8 | 1.8 | 1.8 | kg/person | 0.005 | 0.005 | 0.005 | 0.005 | $m^3$/person |
| Hygiene Supplies (Consumables) | 0.3 | 0.3 | 0.3 | 0.3 | kg/person/day | 0.002 | 0.002 | 0.002 | 0.002 | $m^3$/person/day |
| **Clothing** | | | | | | | | | | |
| Clothing (4 wk = 69 kg; 6 wk =99 kg; 90 d = 214kg) | 99 | 69 | 69 | 214 | kg/person | 0.336 | 0.224 | 0.224 | 0.720 | $m^3$/person |
| Washing Machine | 100 | 100 | 0 | 0 | kg | 0.15 | 0.15 | 0 | 0 | $m^3$ |
| Clothes Dryer | 60 | 60 | 0 | 0 | kg | 0.20 | 0.20 | 0 | 0 | $m^3$ |
| **Recreational Equipment & Personal Stowage** | | | | | | | | | | |
| Personal Stowage | 50 | 25 | 10 | 25 | kg/person | 0.75 | 0.38 | 0.19 | 0.38 | $m^3$ |
| **Housekeeping** | | | | | | | | | | |
| Vacuum Bags | 0.02 | 0.02 | 0.02 | 0.02 | kg/day | 2.0E-05 | 2.0E-05 | 2.0E-05 | 2.0E-05 | $m^3$/day |
| Vacuum (Prime + 2 spares) | 13 | 13 | 13 | 13 | kg | 0.07 | 0.07 | 0.07 | 0.07 | $m^3$ |
| Wipes for housecleaning | 0.30 | 0.30 | 0.15 | 0.30 | kg/person/day | 0.002 | 0.002 | 0.001 | 0.002 | $m^3$/person/day |
| Trash Compactor/Trash Lock | 150 | 150 | 0 | 150 | kg | 0.15 | 0.15 | 0 | 0.15 | $m^3$ |
| Trash Bags | 0.1 | 0.1 | 0.1 | 0.1 | kg/person/day | 0.0001 | 0.0001 | 0.0001 | 0.0001 | $m^3$/person/day |
| **Operational Supplies & Restraints** | | | | | | | | | | |
| Operational Supplies(diskettes, ziplocks, velcro, tape .... | 20 | 20 | 10 | 20 | kg/person | 0.002 | 0.002 | 0.001 | 0.002 | $m^3$/person |
| Restraints | 100 | 50 | 25 | 100 | kg | 0.54 | 0.27 | 0.135 | 0.54 | $m^3$/kg |
| **Maintenance:all repairs in habitable areas** | | | | | | | | | | |
| Hand Tools and accessories | 300 | 200 | 100 | 200 | kg | 1.00 | 0.66 | 0.33 | 0.66 | $m^3$ |
| Spare Parts and Consummables | -- | -- | -- | -- | | -- | -- | -- | -- | |
| Test Equipment (Oscilloscopes, Gauges, etc.) | 500 | 300 | 50 | 100 | kg | 1.50 | 0.9 | 0.15 | 0.3 | $m^3$ |
| Fixtures, Large Machine Tools, Gloveboxes, etc. | 1000 | 600 | 50 | 50 | kg | 3.00 | 1.8 | 0.15 | 0.15 | $m^3$ |
| **Photography** | | | | | | | | | | |
| Equipment (still & video cameras, lenses, etc.) | 120 | 120 | 120 | 120 | kg | 0.30 | 0.30 | 0.30 | 0.30 | $m^3$ |
| Film (Assumes All Digital Approach) | 0.00 | 0.00 | 0.00 | 0.00 | kg | 0.00 | 0.00 | 0.00 | 0.00 | $m^3$ |
| **Sleep Accommodations** | | | | | | | | | | |
| Sleep Provisions | 9.00 | 9.00 | 9.00 | 9.00 | kg/person | 0.10 | 0.10 | 0.10 | 0.10 | $m^3$/person |
| **Crew Health Care** | | | | | | | | | | |
| Exercise Equipment | 145 | 145 | 145 | 145 | kg | 1.90 | 1.90 | 1.90 | 1.90 | $m^3$ |
| Medical/Surgical/Dental Suite | 1000 | 500 | 15 | 250 | kg | 2.50 | 1.25 | 0.15 | 0.63 | $m^3$ |
| Medical/Surgical/Dental Consummables | 500 | 250 | -- | 125 | kg | 1.25 | 0.63 | -- | 0.32 | $m^3$ |

## Key Technology Questions for Long Duration Missions

- How do we preserve food for up to 5 years so that we can provide an adequate, palatable, nutritionally-complete diet in exploration missions?
- How do we perform housekeeping and trash management without contaminating either the external or internal environments?
- What technologies should be used for trash stabilization, compacting, and treatment?
- What types of tools and facilities should be supplied to permit the range of 0-g and partial-g repairs expected? Gloveboxes, tools for plumbing, de-
- How do we provide adequate food preparation and food service facilities that will work in both 0-g and partial-g environments (such as Mars' 3/8-g and the Moon's 1/6-g), including freezers, ovens, utensils, dishwashers, etc.?
- How do we control dust in the surface habitat, especially planetary dust that is tracked in? Can we devise vacuum cleaners that will work in that environment?
- What methods and hardware are best suited for partial and whole body cleansing in 0-g and partial-g?
- How do we develop recreational hardware and activities that reinforce the astronaut's mental and emotional bond to Earth and to its culture, civilization and society — especially methods and technologies which can bring familiar Earthly

| | |
|---|---|
| soldering, milling, sawing, manufacture of small parts and other repair activities? | pursuits, interests, and experiences into deep space? |
| • How can we best use virtual reality, virtual environment, augmented reality, and similar technologies to assist with maintenance activities and continual in-flight training exercises? With recreation? | • How can we provide an intra-vehicular maintenance system that can keep critical systems alive for the required duration? To what extent can expert systems and other technologies support repair? |
| • What methods of noise reduction would be best to use in crew compartments? Active or passive noise cancellation techniques? | • How would a 0-g/partial-g clothes washer/dryer be constructed? |
| • Can we develop technologies for digital image capture, compression and transmission that will meet the scientific, recreational, and public affairs needs of future exploration missions? | • Can we use in-flight recycling of materials (e.g., plastics, solvents, etc.) to save mission mass? For example, on the out-bound voyage, could we re-melt the tons of food packaging plastics to form it into erector set like pieces for tables racks, etc., that are only needed in a gravity environment? |

## 27.0 Crew Composition (Rudisill and Griffith)

**TBD**

## 28.0 Plant and animal factors (Joshi-plant; Tri-animal)

**Animals**

The inclusion of animals—primarily as laboratory specimens—in a spacecraft environment imposes several challenges. The animals contribute to the consumption of life support resources and the production of metabolic wastes and must be factored into the sizing of the life support system. The consumption/production rates vary widely, depending on the species of the animal, and fluctuations due to reproduction and mortality must be taken into consideration. Waste system maintenance and collection considerations are not insignificant—especially in the microgravity environment.

The potential exists in far-term missions, such as a mature planetary base, that animals could be included as a source of food for the crew. These animals likely would mainly consist of marine life, such as fish or shrimp, which could more easily be contained and transported than typical terrestrial livestock.

**Plants/Biomass Production**

An Evolved Mars Base, will probably utilize higher plants to provide full water regeneration and atmospheric revitalization plus a significant portion of the crew's food. Thus, the Biomass Subsystem raises higher plants that provide the primary air revitalization and water recovery functions in the absence of duplicate primary processors. More specifically, the plants, through photosynthesis, consume atmospheric carbon dioxide to produce biomass and oxygen, thus fulfilling the primary air revitalization task. Further, plants filter organic compounds from slightly processed grey water and urine mixed with the hydroponic solution, returning transpirate to the Water Subsystem for final polishing. To fully revitalize the crew cabin atmosphere, the crops also provide at least half, by mass, of the crew's diet (Drysdale, *et al.*, 1999). When the Biomass Subsystem produces sufficient oxygen beyond the crew's metabolic requirements, the Waste Subsystem may oxidize solid wastes.

Staple crops that supply mainly carbohydrate, such as sweet potato, wheat, and white potato, more efficiently generate edible dietary mass on a per photon, per volume, and per time basis than other crops. Crops that supply protein and fat, such as peanut and soybean, are relatively inefficient at generating edible dietary mass. Further, while some salad crops are fairly efficient, the dietary intake from these crops is typically low. Based on Behrend and Henninger (1998), the assumed salad crops are cabbage, carrot, chard, fresh herbs, lettuce, onion, spinach, and tomato. Thus, for flight systems that allow or require some resupply, it appears most expedient to grow the crew's dietary carbohydrate and some salad crops while providing protein and fat by resupply from Earth.

The Biomass Subsystem hardware includes a plant chamber and supporting equipment. Plants grown within the plant chamber consume carbon dioxide from human metabolic activities and other sources. As products, the plant chamber provides edible biomass to the Food Subsystem, oxygen to the Air Subsystem, and clean transpirate to the Water Subsystem. An oxygen scrubber concentrates oxygen from the plant chamber, passing it to the crew cabin. To control the atmospheric temperature and humidity, an anti-microbial condensing heat exchanger dehumidifies the cabin atmosphere. Condensate passes either to the Water Subsystem for final polishing or is recycled to the nutrient solution tank. Recycling excess condensate within the Biomass Subsystem both reduces the overall load on the Water Subsystem and helps to dilute incoming grey water sent from the Water Subsystem. In this arrangement, the Biomass Subsystem provides both the primary air revitalization and water purification functions. Inedible biomass passes to the Waste Subsystem.

Under the ALS Straw Man concept, the Biomass Subsystem utilizes completely artificial lighting for crop growth. Further, lighting photoperiod, photosynthetic photon flux levels, and biomass production module environmental conditions are set to maximize crop productivity as a function of time. Alternative formats for this scenario consider using natural lighting for biomass production.

**Partial pressures of carbon dioxide and oxygen**:

To promote high crop productivity, the nominal atmospheric composition for the biomass production modules maintains the carbon dioxide partial pressure at 0.12 kPa and the partial pressure of oxygen at 17.27 kPa. This latter value for oxygen provides sufficient oxygen partial pressure within the biomass production modules to support crew accessibility (Lange and Lin, 1998). This minimum oxygen partial pressure allows for reasonably timed crew acclimation, except for the case of maximum oxygen uptake such as during hard work (Waligora, *et al.*, 1994). The remaining biomass production module atmospheric constituents are water vapor and an inert gas, such as nitrogen.

**The minimum growing area that is required to grow plants assuming the following closure levels:**

Total closure

This depends on the available lighting, but based on the BPC tests using moderately high irradiance we typically estimate that 40-50 $m^2$ of growing area (continuously planted and harvested) would provide the daily caloric needs for one human, as well as the $O_2$ for the human and any "waste" carbon oxidation back to $CO_2$. Results from the Russian BIOS-3 studies using higher irradiance came out with a value of about 40 $m^2$. Bugbee and Salisbury estimated that this could be reduced to less than 20 $m^2$ using wheat and very high irradiance (which wheat can tolerate). Also note that these estimates do not account for a complete diet (i.e., all the minerals, micronutrients, etc.). It would probably be more practical to supply these from Earth .

50% closure

This would be a simple division if you consider all the factors (i.e., 50 $m^2$ / 2 = 25 $m^2$ ), except if you consider different versions where you don't use oxygen for recycling (oxidizing the waste biomass).

For example, with 20-25 $m^2$ you could provide half of the dietary energy (food) and all of the $O_2$ if you just stabilize or throw out the inedible biomass. The plants would still have sufficient $CO_2$ from the humans, who would be getting half of their food from the plants, and half from stowage. (Note from a resource recovery perspective, this doesn't necessarily preclude recycling nutrients, which can be achieved with relatively rapid processing with bioreactors, before significant biomass oxidation occurs)

2) **Power Requirements assuming the following closure levels**

Total closure

A high irradiance of 1000 $\mu$mol $m^{-2}$ $s^{-1}$ is equivalent to ~ 200 W $m^{-2}$ of irradiance. Assuming a lamp efficiency of ~20% (includes electrical conversion, reflector efficiency, and crop interception), this would indicate that you need ~ 1 kW to provide high lighting for each $m^2$ of crop growing area; thus for 40-50 $m^2$, this would equate to 40-50 kW of electrical power for lighting. As a rough estimate, you might double this to account for cooling, water pumps, fans, etc. Final sum, ~100 kW person for 100% closure. Of course this changes significantly if you can use direct lighting some how (e.g., solar collectors, "greenhouses", etc.)

50% closure
50 kW per person

Salad machine

This will depend on the size of the system and the light intensity, but based on the current thinking a 5 $m^2$ system might be sustained with 5 kW (based on the use of lower light intensity), and a 10 $m^2$ system would be 10 kW.

3) **$CO_2$ levels**

Ambient
The optimum for most C3 plants (which encompasses all of the ALS crops) typically ranges from 1000 to 2000 ppm at 1 atm pressure (101 kPa). On a partial pressure basis, this would equate to a pCO2 of 0.1 to 0.2 kPa.

Minimum tolerated without compromising growth
Acceptable growth can be sustained at 400 ppm (0.04 kPa), which is perhaps 75% of that obtained at 1000 ppm, but the growth drops off linearly below this. Note C4 plants (e.g., corn, sorghum, sugar cane) can sustain good growth well below this, perhaps down to 150 ppm.

Maximum tolerated without compromising growth

We don't as much here, but some species show drops in yield (10 to 25%) at 5000 ppm (0.5 kPa), while others show no effects. It gets a bit worse at 10,000 ppm (1.0 kPa) for the susceptible species. As a rough guide for now, $CO_2$ below 5000 ppm (0.5 kPa) are desirable assuming we select crops that might be more tolerant of these levels. There are also some peculiar effects on leaf stomatal conductance (transpiration) rates at these super-elevated levels, but again it varies with species.

4) **Oxygen levels**

Ambient

Less is known here, but if $CO_2$ is elevated to 1000 ppm, then the 21% (21 kPa) normal ambient is probably the safest bet. Dropping the $O_2$ down to 10% (10 kPa) or even 5% (5 kPa) should not affect photosynthesis, but could affect shoot tissue respiration during dark cycles and root respiration at any time of day. Since DO is a linear function of the pO2 above the water (nutrient solution), and hyrdroponic growers usually like to keep the DO above 2-3 ppm, I think you should probably keep at least above 5% (5 kPa). Normal saturated DO below 21% is ~8-9 ppm (I think).

Minimum
5% (5 kPa)

Maximum
25% (25 kPa), Here the concern is probably more one of fire safety the physiological. Again, so long as the $CO_2$ can be maintained at 1000 ppm, otherwise increases in $O_2$ will depress photosynthetic rates of C3 crops.

5) **Lighting**

Minimum
Depends on crop, but one can still get minimal growth of some crops at 150 $\mu$mol $m^{-2}$ $s^{-1}$

Maximum
Grasses like wheat and rice, maybe up to 2000 $\mu$mol $m^{-2}$ $s^{-1}$ . Broad leaf crops , maybe up to 1000 $\mu$mol $m^{-2}$ $s^{-1}$

Ambient
Optimal for a range of crops and reasonably high productivity, perhaps 600-800 $\mu$mol $m^{-2}$ $s^{-1}$

6) **Maintenance Issues**

Air quality
Control of volatile organics, especially ethylene gas, at least below 50 ppb.

Watering systems
Although some spp. of bacteria are beneficial to plant and can provide for essential plant nutrients through symbiotic relationships, monitoring of the nutrient solutions/ plant growth substrates for plant pathogens is essential. Effective countermeasures for pathogen control is also essential.

Human Access and Automation (RKF) – While automation will hopefully address much of the burden of plant tending, hands on human involvement is foreseen. Besides correction of automation failures, the active handling and caring for plants is of considerable psychological benefit. Assuming that human access is worthwhile, it is proposed that a low pressure greenhouse should be entered with the volume pressurized to 5psi while wearing a mask delivering 100% O2. While this will impact greenhouse structural strength/mass, it avoids the time, risk, awkwardness and fatigue of wearing a pressurized EVA suit for normal greenhouse support. The benefits and costs of this approach have yet to be adequately confirmed.

Planetary Contamination (RKF) – Providing direct access to the greenhouse by shirt sleeved O2 masked crewmembers will simplify the operations for minimizing the risks of forward and backward biological contamination. Direct linkage of the habitat to greenhouse is recommended.

**Research needs (Revolutions desired)**

- Management of the nutrient delivery systems in microgravity and partial gravity.
- Recycling of sodium in enclosed life support systems
- Production of high yielding variety of candidate crops
- Increasing the yield ratios (edible/inedible plant biomass ratio).

## 29.0 Science (Stilwell and Charles)

**TBD**

## 30.0 Emergency response provisions (RKF)

To respond to off-nominal conditions and protect crew health, mission and vehicle architecture must address several scenarios :

- Fire/smoke detection, non-toxic suppression and byproduct cleanup
- Cabin depressurization detection, chamber isolation, exact cause determination/location, initial resealing, repressurization and long term repair/verification
- Particulate, chemical and biological contamination detection and cleanup
- Contingency consumables to allow time for failure correction or mission extension due to resupply/return skip cycle
- Early return for untreatable health or vehicle emergency
- Single vs dual escape paths
- Alternate ingress path preservation

## 31.0 Recommendations

**TBD**

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## APPENDIX A – ANTHROPOMETRY AND BIOMECHANICS (Rajulu)

Human body size (linear, areal, and volumetric), range of joint mobility, locomotion/translation capability, physical strength capabilities (whole body, upper arm, hand, lower limb, etc) functional strength capabilities (ratcheting, cranking, arm pushing/pulling, leg lifting/lowering, wheel turning, upper body and lower body exertions, etc) are important physical characteristics that constitute human requirements for the space program.

Body size variations are essential for designing cockpit seating, EVA suits, escape suits, tool and hardware dimensions.

Range of joint mobility needed to perform tasks such as hammering, kneeling, climbing, running is necessary for designers to understand the specifications for designing clothes, suits, hardware for micro-, partial gravity environments.

Locomotion/translation capability /limitation under suited conditions is a necessary data for suit designers to design the suits or space clothes with necessary flexibility.

Physical strength capabilities/limitations and functional strength characteristics under suited as well as unsuited conditions in reduced gravity environments is essential for hardware designers and mission planners.

Unfortunately, much of the data on anthropometry and biomechanics data is based on earth gravity and even the earth gravity data is outdated since much of the data was gathered in the 70s and is limited since it do not address issues pertaining to reduced gravity environments.

There is also a need to understand the cost and benefit aspects of accommodating a 5$^{th}$ percentile Japanese female and a 95$^{th}$ percentile American male. Such a wide spectrum of variation in strength and physical dimensions will undoubtedly increase the cost of manufacturing suits, hardware, tools, etc. There is also a misconception that a 5$^{th}$ percentile person in stature is also a 5$^{th}$ percentile in arm reach or in shoulder strength.

Hence, there is a tremendous need to represent the anthropometric and strength data adequately and logically so that the designers, engineers and program managers and policy makers can make sound policy decisions, design better suits and hardware.

### Cost/benefits Analysis

The goal of NASA is to develop space hardware that would accommodate any personnel whose physical dimensions and strength characteristics fall within a 5$^{th}$ percentile Japanese female and a 95$^{th}$ percentile American male. Unfortunately, the amount of resources needed to build hardware to accommodate such a wide spectrum might not be available for NASA to achieve its objectives of space exploration. Hence, a cost/benefits analysis will also be conducted to enable policy makers in making decisions on what physical requirements they would be able to accomplish with the amount of resources they are able to procure for NASA. In addition to providing the 5$^{th}$ percentile Japanese and the 95$^{th}$ percentile American male capabilities and limitations, this requirement document will also provide variable options for NASA so that it can select the appropriate requirements for designers that would meet the amount of resources available.

### Physical Dimensions

#### Linear Dimensions

In this section, tables will be provided which shows the 5$^{th}$ and the 95$^{th}$ percentile values for all critical uni-dimensions (stature, arm reach, shoulder height, etc.) An effort will be made by the ABF to generate a table with dimensions that are critical for designers. In addition to linear dimensions, a correlation table will be provided which shows for example, the variation of body dimensions (both in percentile as well as actual values) of a $5^{th}$ percentile stature. In other words, this table will show the body dimensional variation of a group of females who represent $5^{th}$ percentile height data. This would allow designers to understand the correlation of linear body dimensions with respect to each other.

Area dimensions

Tables will be provided that will give cross-sectional variation of body segments (such as interscye area, bideltoid area, waist area, thigh area, chest area) which are necessary for designers for designing suits.

Volumetric dimensions

Volumetric dimensions for all major body segments (upper arm, lower leg) as well as for functional body areas (upper torso, whole arm) will be provided here.

Range of Motion

The range of motion of each joint under suited and unsuited condition will be provided for both females as well as males.

Arm Reach – Unrestrained, and Restrained

Arm reach capabilities of unsuited males and females data will be provided for suit development and hardware design and development. The table will include current information on nominal arm reach under unrestrained and restrained conditions.

Foot Reach

Foot reach data for unsuited males and females will be provided for cockpit control designs.

**Strength Characteristics**

Isolated joint strength characteristics

Isolated maximum voluntary strength data along with percentile data for males and females will be given in a tabular form. In addition, maximum capable strength requirements for a $5^{th}$ percentile female and the maximum allowable strength capabilities of a $95^{th}$ percentile male will be established.

Functional strength characteristics

The functional skills that are needed to perform as a crewmember will be identified and the minimum capabilities of a $5^{th}$ percentile female will be established and presented in a tabular form.

Gravity Effects

Much of the anthropometric and strength data will be based on Earth gravity environment. Wherever possible, tables of these data pertaining to reduced gravity will be provided. In addition, a matrix will be generated which will show both the current status of these data and the areas where there is a need to generate or gather such data.

## APPENDIX B – Cabin Pressure (Kosmo)



**BACKGROUND**

The selection of an operational atmosphere (representing an acceptable oxygen level and pressure regime) for a space vehicle cabin, in-space or planetary surface habitat or space suit involves consideration of a number of different factors and parameters. Predominant among these is the maintenance of normal physiology of the crewmembers. Other significant factors include operations and logistics, science activities, engineering aspects, as well as cost and safety considerations. The operational atmosphere selected for habitable and functional human space systems must ultimately be a trade-off or compromise between all of the abovementioned factors with perhaps the true drivers being physiological, engineering, and cost considerations together with a close regard for the safety, comfort, and performance capabilities of the crewmembers.

One of the primary purposes of establishing a human presence for the exploration of space, if not the primary purpose, is to allow for the construction and maintenance of fixed based habitats and utilization of scientific equipment to enable exploration via regular, extensive and routine extra-vehicular activity (EVA). Because of the importance of EVA, its extent, and its expense, it is vital to maximize the productivity of the EVA crew. Selection of the atmospheric pressure level and composition has direct critical effects on technology and engineering requirements of the EVA systems and moderate effects on engineering requirements of the life support and thermal control systems of the space craft cabin and habitat elements.

## HISTORICAL PERSPECTIVE

A brief summary overview of historical experience for space habitat and space suit atmospheres is presented in Table 1. As seen in the table, extensive space experience has been gained with both low and sea-level pressure environments.

Present space vehicles operate at standard sea-level atmospheric pressure, with the Shuttle orbiter reducing the cabin pressure to 70.3 kPa (10.2 psia) to facilitate EVA operations. The International Space Station (ISS) also operates at the nominal sea-level pressure to maintain compatibility with the Shuttle orbiter and the Russian Soyuz vehicles as well as to maintain a “control” atmospheric environment for conducting material and biological experiments in the micro-gravity environment. Unlike the Shuttle orbiter, the ISS accommodates EVA operations without decreasing cabin or habitat pressure but requires a rigorous prebreathe protocol coupled with airlock operational procedures.

In previous space programs, habitat pressures have ranged from 34.5 kPa (5.0 psia) to the current 101.4 kPa (14.7 psia) while corresponding space suit system pressures to support these space missions have ranged from 26.2 kPa (3.8 psia) to 40.0 kPa (5.8 psia) as used by the Russians with their Orlan version EVA suit for support of previous MIR station operations and currently, for ISS support. It should be noted that prototype advanced space suits have been developed by NASA to operate at 57.2 kPa (8.3 psia) in order to eliminate extensive overhead prebreathe operations.

For short duration missions of two weeks or less, 100% oxygen atmospheres at pressures up to 34.5 kPa (5.0 psia) have been utilized (e.g., Mercury, Gemini, Apollo missions). Skylab also used a 34.5 kPa (5.0 psia) pressure regime but was a mixed atmosphere of 70% oxygen and 30% nitrogen. The longest Skylab mission was 84 days .

Russian spacecraft (e.g., Salyut, Soyuz, MIR) environments have utilized mixed oxygen-nitrogen atmospheres all at sea-level pressures. For EVA operations this environment can present a higher level of risk of the crewmembers encountering the possibility of decompression sickness (“bends”) unless some element of compromise is established between the amount of prebreathe time at 100% oxygen versus space suit operating pressure both of which are contingent upon the vehicle cabin or habitat pressure. In the case of Russian EVA operations and based on extensive ground-based altitude chamber testing of over 500 subject runs, the Russian EVA operations are conducted with a suit pressure of 40 kPA (5.8 psia) and only a 40-60 minute of 100% oxygen prebreathe time. Although this posses a slightly higher “bends ratio” risk, their ground-based test results coupled with their extensive EVA operational experience, makes this a manageable and acceptable risk.

Operational values for the decompression ratio, R; (aka, “Bend’s Ratio”), have historically ranged from zero to 1.84 and driven by cabin atmosphere levels (based on the concentration of oxygen and pressure regime), prebreathe timelines, and corresponding operational pressure level of the space suit. All space suit systems to date have utilized 100% oxygen atmospheres ranging in pressures from 26.2 kPa (3.8 psia) to 40.0 kPa (5.8 psia).

It should be noted that adjustments to vehicle cabin or habitat pressures and subsequent prebreathing operations consume crewmember time, impacts requirements for support equipment, and correspondingly effects overall mission overhead and productivity. It would appear that it is highly desirable or mandatory to minimize or eliminate these operational requirements in future space missions where EVA may be a frequent or routine function.

The ability of the crew to move quickly and efficiently between the vehicle cabin, habitat, and space suit atmosphere environments is important for crew safety, productivity, and overall mission success.

**Table 1. Historical Space Program Habitat and Spacesuit Atmospheres**

| Program | Crew Stay in Habitat (days) | Habitat Atmosphere: Total Pressure (kPa / psia) | Habitat Atmosphere: Percent Oxygen | Spacesuit Atmosphere (Pure Oxygen): Total Pressure (kPa / psia) | Decompression: O2 Prebreathe (minutes) | Decompression: Bends Ratio R=(ppN2/Suit Pressure)* | Rationale for Habitat Atmosphere Selection |
|---|---|---|---|---|---|---|---|
| Mercury | <2 | 34.5 / 5.0 | 100 | – | – | – | Low vehicle mass. Reliability. Adequate air cooling. Physiological compatibility for short missions. |
| Gemini | 12 | 34.5 / 5.0 | 100 | 26.2 / 3.8 | – | 0 | See Mercury above. |
| Apollo | 12 | 34.5 / 5.0 | 100 | 26.2 / 3.8 | – | 0 | See Mercury above. |
| Skylab | 84 | 34.5 5.0 | 70 | 26.2 / 3.8 | – | 0.4 | Long duration crew stays necessitated reduced oxygen pressure for physiological reasons. Commonality with Apollo drove total pressure. Nitrogen selected as diluent based on some evidence that it may be physiologically beneficial as opposed to other potential diluents. |
| Shuttle: Normal | 10 | 101.4 / 14.7 | 21 | 29.6 / 4.3 | 240 (contingency) | 2.7 reduced to 1.7 by contingency EVA prebreathe | Low development cost. |
| EVA Prep. | 1 | 70.3 / 10.2 | 28-31 | 29.6 / 4.3 | 40 | 1.77 reduced to 1.65 by prebreathe prior to EVA | Increased crew productivity during EVA preparation. |
| Russian spacecraft | 366 | 101.4 / 14.7 | 21 | 40.0 / 5.8 | 40-60 | 2.0 reduced to 1.84-1.78 by prebreathe prior to EVA | Assumed: low technology development requirements. |

*** Based on a controlling tissue compartment with a half time for inert gas elimination of 360 minutes.**

## SELECTION CONSIDERATION FACTORS & PARAMETERS

The following subsections are presented in the form of short synopsis or vignettes of various attributes, consideration factors, parameters and constraints that influence the design and selection of space vehicle cabin, habitat, and space suit atmospheres.

### HUMAN PHYSIOLOGY

-HYPOXIA :

In terms of the well-being of the crew, the most significant gas component in the atmosphere is oxygen. The partial pressure of oxygen at sea-level on Earth is 21.0 kPa (3.06 psia). As the atmosphere is breathed, its components are diluted in the lungs by the addition of carbon dioxide and water vapor so that at the alveoli where oxygen transfer to the blood takes place, oxygen partial pressure is 13.8 kPa (2.01 psia). The lower limit of oxygen concentration is bounded by the physiologic impact of hypoxia. Although ambient oxygen pressure decreases with increased altitude as does alveolar oxygen pressure, the human body through the process of acclimatization, can adapt (within limits) to a hypoxic environment and increase the lung's alveolar oxygen pressure.

A pressure of 25.8 kPa (3.75 psia) with 100% oxygen is required to maintain the lung alveolar pressure for the human body's blood oxygen saturation to be equivalent to sea-level. A sea-level equivalent atmosphere can be achieved between 25.8 kPA (3.75 psia) and 101.2 kPA (14.7 psia) by altering oxygen and nitrogen concentrations without seriously affecting physiological responses.

For total cabin pressures above 25.8 kPa (3.75 psia), the oxygen partial pressure can be controlled between 17.9 kPa (2.6 psia) and 34.5 kPa (5.0 psia) which is used to vary the oxygen percent by volume in the atmosphere. Based on Skylab astronaut experiences in the 34.5 kPa (5.0 psia) environment (70% oxygen ; 30% nitrogen), they could go from a ground-based sea-level launch environment to the 34.5 kPa (5.0 psia) environment of the Skylab cabin and be unable to tell the difference as far as energy expenditure and alertness are concerned. The Skylab crews operated at this low pressure and atmosphere composition with only the following subjective responses noted or observed :

- Lack of convection results in a warm feeling because the rate of heat rejection is reduced.
- Reduced boiling point of water causes a cold feeling after showering due to rapid evaporation of water.
- Experienced rapid evaporation of sweat during exercise – a definite plus for body cooling.
- Lower air density reduced voice projection (made whistling difficult).

From the above discussion, although oxygen pressures significantly below sea-level equivalent values induce hypoxia, an operational method for reducing the potential impacts of the effect would be to naturally acclimatize the crew over a long duration mission to lower physiologically acceptable oxygen pressure levels. Prolonged exposure to low oxygen levels in the hypoxia zone requires acclimatization which can be part of normal adaptations required for long duration space missions.

Many physiological changes associated with long duration space missions represent normal body adaptations in order to establish a homeostasis appropriate to the new environment.

- OXYGEN TOXICITY :

The upper limit of oxygen acceptability is bounded by central nervous system toxicity above about 2.5 ATM (36.8 psia). For oxygen pressures from about 2.5 ATM to 0.5 ATM (7.35 psia), pulmonary oxygen is limiting. At oxygen pressures below 0.5 ATM (7.35 psia) the limitation is uncertain but there can be long-term limitations relating to reduction in circulating blood mass. Symptoms of oxygen toxicity appear dependent on both the oxygen partial pressure and time of exposure. This potential condition would favor lower oxygen concentration levels without placing the crew in a hypoxia zone. Also to consider is the fact that oxygen concentration is critical to the selection of materials used inside the cabin, habitat, and space suit environments. As the oxygen concentration increases, flammability of materials increases. Given concerns for both the oxygen toxicity factor and the flammability factor, lower oxygen pressure regimes would be the selection choice.

- DECOMPRESSION SICKNESS :

Also identified as “Altitude Decompression Sickness” (ADS), this condition results from evolution of nitrogen bubbles in the body after a reduction in ambient pressure. Foe example, a change from a sea-level cabin pressure to a lower space suit pressure is a potential source of ADS if no action is taken to prevent or protect against ADS. Protective measures involve reducing the body tissue nitrogen content by partial equilibrium of the body to a breathing medium of 100% oxygen or an atmosphere containing a reduced partial pressure of nitrogen. Reduction of atmospheric pressure with dissolved diluent gas (nitrogen) in the body results in evolution of gas bubbles in the body tissues. Current U.S. and Russian spacecraft have atmospheres that are very much like that on Earth at sea-level. This is a conservative atmosphere that assures the well-being of the crew, minimizes flammability concerns, and allows microgravity adaptation concurrent without the masking effect of physiologic acclimatization or adaptation that might be imposed by a less benign atmosphere. Since ADS is a manageable concern, and that although a normoxic sea-level pressure is an attractive atmosphere for any mission; a number of alternative “operationally friendly” as well as physiologically safe atmospheres can be proposed for future long-term space missions. It should be noted that the task of the physiologist or physician involved in considerations of atmosphere selection is not to assure that the selected conditions are equal to Earth normal values, but to assure that the atmosphere is physiologically acceptable. Physiologically acceptable approaches that maximize engineering, cost, and safety factors are strongly encouraged.

**OPERATIONS AND LOGISTICS**

- EVA PREBREATE TIME :

EVA appears to be particularly provocative of ADS because of sustained activity and the duration of exposure. Current U.S. space suit systems (Shuttle/ISS) operate at 29.6 kPA(4.3 psia) after either a 4-hour 100% oxygen prebreathe time or a 24-hour protocol involving a staged cabin decompression from 101.4 kPa (14.7 psia) to 70.3 kPa (10.2 psai) and a 40-minute oxygen prebreathe. The Russian EVA space suit system operates at a nominal pressure of 40.0 kPa (5.8 psia) from a 101.4 kPa (14.7 psia) cabin environment after a prebreathe time of between 30-40 minutes. Russian investigators have studied and verified long staged pressure exposures through extensive ground-based chamber test activities, but they have not required or used long pressure reduced stages to allow lower suit pressures while in flight. Both the U.S. and Russian prebreathe procedures would appear to involve some risk of ADS, however; there have been no reports of occurrence of ADS during EVA operations in either the U.S. or Russian space programs.

- EVA CREW PERFORMANCE :

High crew productivity is essential to both IVA and EVA operations. Perhaps more so as longer space missions and future planetary surface exploration activities occur. Specifically, EVA crew time spent in prebreathing oxygen prior to decompression is basically unproductive but may have a corresponding positive influence on productivity during the EVA if it allows a lower-pressure, more mobile space suit and glove system which induces less fatigue in the EVA crewmembers. Many EVA tasks and operations involving high dexterity and/or mobility performance capabilities (especially those tasks and operations involved with future planetary surface operations) may be more difficult to achieve in a high-pressure space suit system (5.8 –8.3 psia range) but relatively easier to achieve in a lower pressure space suit system (3.8-4.3 psia range).

- CREW MOVEMENTS BETWEEN HABITAT ELEMENTS :

If cabin or habitat elements contain atmospheres which differ in pressure or composition, crewmember movement between those elements will be slower, degrading overall mission productivity. Pressure differences would require airlocks which cause expenditure of crew time in hatch operations and pressure changes and could also possibly require prebreathing depending on the pressure differences. Atmospheric composition differences at equal pressures would require air movement barriers or hatches. In this case, the extent of sealing requirement would depend on the significance of the consequences of partial mixing of the two atmospheres due to intermingling during crew passage from one atmosphere to

another. Generally, the more stringent the requirement to reduce mixing, the more crew time may be spent in moving from one atmosphere to another.
Crew safety may be affected by the use of airlocks between cabin or habitat elements. A safety benefit might arise from the availability of these additional isolatable habitable volumes. Correspondingly, a safety disadvantage might be the added time required for crewmembers to move from one element to another during contingencies such as solar flares.

- <u>TRANSFER BETWEEN LANDER & HABITAT</u> :

Crew transfer between a lander vehicle system and a surface habitat may involve decompression, dependent on both of their internal pressures and the operational space suit pressure. If crew transfer between respective elements is effected by EVA, the space suit pressure will be the driver in the requirement for any crew time spent in decompression preparations. If a portable system such as a mobile pressurized module/rover vehicle is used for crew transfer, it will probably be of equal pressure with either the lander crew cabin or surface habitat. The difference in lander and habitat pressures would then determine how much time would be spent in decompression.

Common pressures between the lander crew cabin and surface habitat could eliminate crew transfer decompression time only if a mobile pressurized module/rover vehicle system is used instead of EVA transfer operations.

- <u>HABITAT NOISE LEVEL</u> :

The noise level inside the cabin or habitat will be affected by the atmospheric pressure. Lower pressures are expected to necessitate higher volumetric flowrates of air through the thermal control and life support subsystems, resulting in increased fan and air noise. Habitat noise levels must be low enough to allow audible caution & warning alarms to be heard by crewmembers in all locations of the cabin or habitat. Also, noise levels must not cause degradation of crew productivity due to irritation, sleep disruption, or interference with crew verbal communication.

- <u>CREW VERBAL COMMUNICATION</u> :

Cabin and habitat atmospheric pressure and composition may also affect face-to-face crew communication. Voice efficiency and frequency content are affected parameters. Atmosphere diluents such as helium, which have much lower density than that of nitrogen, produce increased frequency of the voice which, at high helium concentrations, may result in decreased intelligibility.
Another potential diluent gas, argon, has been suggested as a replacement candidate for helium to alleviate the voice communication problems. However, since argon is twice as soluble as nitrogen, this poses corresponding problems related to ADS and may seriously impact EVA-related operations.

Pressures lower than about 69.0 kPa (10.0 psia) will result in degradation of a crewmember’s ability to understand speech transmitted through the atmosphere from a sound source. This was demonstrated by measurements of speech intelligibility during ground-based testing for the Skylab program in a 34.5 kPa (5.0 psia) pressure chamber with ambient noise sources. Speech intelligibility of the Skylab on-orbit crewmembers may have also been affected by facial distortions caused by the zero gravity environment along with the lower pressure environment. Misinterpretation of oral statements caused by facial feature distortion associated with micro-gravity environments has been reported to annoy or upset some crewmembers.

- <u>LOGISTICS</u> :

Logistics considerations of cabin, habitat, and space suit atmospheric pressure and composition include re-supply of oxygen and atmospheric constitution gases. Oxygen and diluent gas must be carried in sufficient quantities as part of the overall mission mass or provided as part of re-supply delivery operations to make up for structural leakage, airlock losses, and contingency decompressions. Since higher atmospheric pressures (whether in cabin, habitat, or space suit
Environments) is the source for potential increased leakage conditions, lower internal pressures would correspondingly result in lower re-supply mass requirements. Other potential methods to reduce logistics overhead requirements might include increasing the percentage of airlock gas recovery during EVA operations, reduce overall cabin, habitat, and space suit leakage sources, and produce makeup gases in-

situ if feasible. Suitable logistic countermeasures for the loss of gas supply should be determined for future long-term space missions and planetary surface exploration where return and/or re-supply may not be possible.

- <u>FLAMMABILITY</u> :

In general, spacecraft related fires will be more easily contained and extinguished in atmospheres which have lower oxygen concentrations. Higher habitat pressures, coupled with lower cooling air velocities, may reduce the rate of combustion by lowering both the oxygen concentration and the rate of supply of oxygen to a fire in an enclosed space such as an electronics cabinet.

NASA materials flammability requirements are contained in NHB 8060.1, Flammability, Odor, Off-gassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion. The basic requirement is that materials are nonflammable or self-extinguishing when exposed to a standard ignition source in an upward flame propagation test (NHB 8060.1 Test 1). Materials that fail this requirement must be restricted in use such that they are nonflammable or non-propagating in the “as used” condition. Flammable materials may be acceptable if located inside a fireproof container with no internal ignition sources that can lead to fire propagation. The acceptability of such a configuration can frequently be determined by analysis, but a standard container flammability test (NHB 8060.1 Tests 8, 9) is conducted when the analysis is inconclusive.

When assessing the flammability of spacecraft materials, ignition sources are assumed to be present; the absence of ignition sources is not in itself justification for acceptance of flammable materials, although it may be used in conjunction with other acceptance rationale. This philosophy was implemented in the aftermath of the Apollo 204 fire and has been the basis for material acceptance for all subsequent U.S. manned space flight programs. The effect of these requirements is to ensure that all major use materials are nonflammable or self-extinguishing. Flammable materials are restricted to minor use and are separated from each other such that they are non-propagating in their “as used” configuration. The following are some general considerations concerning materials selection and atmosphere compositions regarding management of flammability requirements :

- Materials flammability is <u>strongly</u> dependent on oxygen <u>percentage by volume</u> ; <u>weakly</u> dependent upon oxygen <u>partial pressure</u>.
- At constant oxygen partial pressure, materials flammability <u>decreases</u> with increasing total pressure
- Same considerations apply to fire extinguishment
- Materials flammability testing in 1-g environment is considered somewhat <u>conservative</u> for flammability concerns in microgravity environments.

NASA has extensive experience in control of materials flammability in a 30% oxygen, 70.3 kPa (10.2 psia) atmosphere based on Shuttle flight operations. Although roughly 85% of materials are flammable in this environment, sufficient non-flammable materials are available to allow a choice of non-flammable materials for almost all applications. From a strictly flammability standpoint is concerned, the 70.3 kPa (10.2 psia), 30% oxygen environment would be the recommended atmosphere for prime consideration for future long-term space missions. Cost impacts would have to be traded against the increased materials cost for consideration of higher percentage oxygen, lower pressure atmosphere regimes.

**LABORATORY SCIENCE**

- <u>LIFE SCIENCES (ANIMAL & PLANT EXPERIMENTATION)</u> :

Laboratory users who provide experiment packages will experience an increase in requirements for pre-flight testing and verification of their hardware if cabin or habitat pressure less than sea-level is selected. These requirements will be generated by the need for data on science packaging characteristics related to both total pressure and oxygen concentration, such as material off-gassing, flammability, and air cooling.

In addition, ground-based reference experiments (control base-line) should be performed at conditions similar to the actual space flight atmosphere conditions to reduce the number of experimental variables.

Ground-based experiments in high altitude cities (3000 m/10,000 ft.) cities might be used as references for space flight conditions at pressures as low as 70.3 kPa (10.2 psia).

Experimental animal parameters which are known to be affected by habitat pressure and/or composition include but may not be limited to following :

- Antibody production (guinea pig)
- Susceptibility to viral infection (mice)
- Recovery time from infection (mice)
- Gas exchange (chicken egg)

Plant parameters which are known to be affected by habitat pressure and/or composition include but may not be limited to the following :

- Photosynthesis (wheat, rice, soybean)
- Water loss by transpiration
- Production of toxic gases

If a space or planetary surface-based habitat is used to generate life science data under atmospheric conditions significantly different from Earth sea-level, additional ground-based life science research would be required to establish a suitable control database. Development of instruments to measure experimental variables may also be affected by different atmospheric conditions.

- MATERIALS SCIENCES

Materials science experiments may be influenced by cabin or habitat atmospheric pressure and/or oxygen concentration levels. Affected parameters may include but not be limited to the following :

- Use of negative pressure as a method of material containment
- Solubility and/or chemical composition
- Acoustics
- Combustion and chemical reactions
- Heat transfer through surrounding air

- USE OF OFF-THE-SHELF EQUIPMENT :

Use of off-the-shelf equipment will be inhibited by increasingly stringent flight requirements at lower atmospheric pressures and/or higher oxygen concentrations.

- GROUND-BASED EXPERIMENTS :

See "Life Sciences (Animal & Plant Experimentation)"

- PRE-FLIGHT TESTING :

See "Life Sciences (Animal & Plant Experimentation)"

**HABITATION SYSTEMS**

- MATERIALS SELECTION :

See "Flammability"

- AIR COOLING :

The performance of liquid coolant loops in the thermal control system is not affected by the total cabin or habitat atmospheric pressure. However to provide the required air cooling to the crew and heat generating equipment in the cabin and habitat elements, the thermal control system has to flow a certain rate of air mass through the elements, independent of the cabin or habitat pressure. As the total pressure and air density decrease, the required volumetric flow rate of the air cooling subsystem increases. A

similarity analysis shows that the blower power requirement of the air cooling subsystem is inversely proportional to the square of the total cabin or habitat pressure. For example, it normally takes 250-500 W to provide air cooling in an ISS-size habitat module at 101.3 kPa (14.7 psia). The blower power requirement will be doubled to 500-1,000 W at 70.3 kPa (10.2 psia) and quadrupled to 1.0-2.0 KW at 50.6 kPa (7.35 psia). In short, although the thermal control system does not impose a lower limit on the range of the cabin or habitat pressure, the power penalty incurred to the air cooling subsystem practically limits the total pressure to 50.6 kPa (7.35 psia) or
Higher.

- TEST AND VERIFICATION :

Habitat pressure different from sea-level increases complexity and cost of pre-flight performance and certification testing. A method for potentially reducing this effect would be to implement previous program experience base and “lessons learned” for performance and certification test and verification requirements.

**USE OF OFF-THE-SHELF EQUIPMENT**

In addition to the previous comments under “Laboratory Science” regarding the use of off-the-shelf equipment, the following specific parameters are anticipated to be directly affected:

- Materials selection (off-gassing, oxidation/corrosion, flammability)
- Air cooling of equipment (velocity and density)
- Sound levels (noise production from fans and sound transmission)
- Certification and verification (pre-flight testing at operational conditions)
- Commonality with other space program equipment (equipment design)

**LIFE SUPPORT**

- PLANT GROWTH :

Plant growth for life support and/or food production may be affected by the habitat atmospheric pressure and composition in several ways. Photosynthesis, transpiration, and release of toxic gases all vary in relation to pressure, oxygen concentration, or carbon dioxide concentration. Carbon dioxide concentration has an effect on plant growth, with enriched carbon dioxide/low oxygen concentration atmospheres producing higher photosynthesis rates. Wheat germination and early growth under atmospheric pressures as low as about 6.0 kPa (0.87 psia) have been shown to be possible. However, under these conditions, seedling characteristics such as leaf size and chlorophyll content were significantly lower than those of control seedlings grown under Earth atmospheric conditions. Germination rate was significantly lower except when the atmosphere was composed of 99.1% oxygen. Oxygen is required for wheat germination and growth during its pre-photosynthetic phase. Also, microorganism activity, ecology, and population dynamics may be affected by habitat atmospheric pressure and composition. Bio-engineering of plant growth characteristics to accommodate appropriate atmospheric pressures and concentrations suitable to future space missions should be considered.

- ANIMAL GROWTH :

Although not fully understood or investigated to any certain conclusion, food crop animal growth may also be affected by habitat atmospheric pressure and/or composition. Known effects on laboratory animals were identified previously in this document under “Life Sciences (Animal & Plant Experimentation).

- RE-HUMIDIFICATION :

Life support subsystem heat exchangers for removal of atmospheric humidity will tend to over condense the humidity at atmospheric pressures substantially lower than 70.3 kPa (10.2 psia).
An additional non-condensing heat exchanger or water spray re-humidifier may be required for low habitat pressures. Heat exchangers designed specifically for planetary surface habitats however will not necessarily have this tendency.

- THERMAL CONTROL :

In addition to comments regarding AIR COOLING in the previous section under “HABITATION SYSTEMS”, cooling fan power and potentially its size, must be increased at reduced atmospheric pressures in order to maintain equal mass flow rate. Mass and volume of air cooling components such as fans, ducts, and filters are increased in size at reduced atmospheric pressures in order to maintain equal pressure drop with the increased volumetric flow rate. In general, the thermal control system would not have to physically change greatly if the cabin or habitat could afford the extra power for lower atmospheric pressures.

**HEALTH CARE**

Habitat atmospheric pressure and composition may affect health care system hardware and operations in the following ways.

Health care systems will be used to monitor the health ststus of individual crewmembers and to treat resultant medical problems. Health care systems will provide capability to measure and monitor physiologic variables associated with worl capacity, lung function, blood chemistry, tissue oxygenation , immune system function, and other physiologic functions affected by the respirable atmosphere. Effects of changes in respirable atmosphere pressure or composition during a mission may be expected to be investigated and monitored during the mission planning and design phase as part of the overall health care systems management operations. Examples of changes to which crew-members may be subjected that may affect long term health, ability to perform immediate tasks, or survival are changes in pressure, oxygen concentration, carbon dioxide concentration, (inert) diluent gas concentration, dust or particulate material, temperature, and water vapor upon moving from one mission task to another or from one mission environment to another.

Countermeasures for known or potential deficiencies in respirable atmosphere design will need to be incorporated into the health care systems. For example, appropriate prebreathe protocols and monitoring instrumentation should be provided if needed to minimize risk of ADS and related disorders due to transition from the (normal) ambient cabin or habitat pressure regime to a significantly lower space suit pressure for EVA operations. To assist adaptation to respirable atmosphere pressure and/or composition changes within or between habitable pressurized volumes, adaptation protocols and monitors may be developed as part of technology or advanced development projects to facilitate these operations. Areas within planet surface habitats or vehicle cabins may need to have special dust, humidity, or gas composition control if necessary to meet crew health needs.

Medical care will include the capability to rescue and resuscitate crewmembers incapacitated by a problem, deliver oxygen therapy, ventilation support, provide fluid therapy, perform emergency surgery, provide intensive care, hyperbaric treatment, and respiratory therapy while in a suitable respirable atmosphere environment. In perhaps the case of other than standard sea-level environments, some current terrestrial-based medical diagnostic and application practices may need to be modified. Baseline data will need to be established and collected as part of technology and advanced projects to differentiate normal physiologic adaptation to an abnormal environment from intrinsic pathophysiology. Physiological research will be necessary to determine points at which changes in atmospheric parameters produce adverse effects in humans.

**CREW ACCOMMODATIONS**

- FAN POWER :

See “HABITATION SYSTEMS/Air Cooling”

- CONSUMABLES PACKAGING :

The design of packaging for crew consumables such as food is also affected by the difference between Earth sea-level pressure and cabin or habitat pressure. If a sea-level facility is used for packaging consumables for launch, the trapped air will exert pressure on the packaging materials when exposed to a lower habitat pressure. Some foods can be vacuumed-packed, preventing this effect, but other foods, such as bread, cannot be vacuumed-packed without destroying their palatability. Frozen foods are also packaged with an air-filled ullage space. Earth-based food packaging for habitat pressures much lower than sea-level could require construction of specialized food production and packaging facilities on Earth which would be at the habitat pressure. Foods would then be produced, packaged, transported, and stored for use at the same ambient pressure. Such a food preparation facility would be expensive to construct and operate.

- FOOD COOKING TIME :

Lower habitat pressure lowers the boiling point of water and food substances. The reduced pressure impacts food recipes and increases cooking times. The relationship of cooking time to temperature is food-dependent. For cooking of in-situ produced food, crew time required for food production will increase with lower habitat pressures, potentially affecting IVA crew productivity. Pressure-cooking of some foods can reduce preparation times by cooking inside a pressurized container.

Generally, prepared food items are heated below the boiling point of water and served around 60 degrees C (140 degrees F), which deters the growth of microorganisms. Food-borne illness is caused by microorganisms and is the chief concern for the health and safety of the crew. All microorganisms are killed by heat, if the temperature is high enough and is applied for a sufficient length of time. The relationship of destruction time to temperature is microorganism-dependent. The destruction temperature ranges from 60 degrees C (140 degrees F) for vegetative bacteria to 121.1 degrees C (250 degrees F) for heat-resistant spore forming bacteria.

**STRUCTURES AND MECHANISMS**

- PRESSURE SHELL MASS

Cabin and habitat atmospheric pressure and composition may affect structures and mechanisms subsystem hardware and operations in the following ways. Pressure vessel design may be more severe for higher pressure regimes; seals around hatches and penetrations will be subject to higher loads and will require closer design tolerances to reduce leakage. In this instance, higher internal atmospheric pressure requires more exacting design and tolerance factors. Pressure vessel mass may be affected by internal pressure in some cases; pressure vessel requirements are related to internal atmospheric pressure, but other considerations such as launch and landing loads may also drive the thickness. In the case that internal pressure becomes a pressure wall driver, increase pressure will result in a higher structural mass. On the other hand, use of the cabin or habitat internal atmospheric pressure as a means of structurally stiffening for launch and landing may be beneficial in terms of overall mass savings. In this case, higher internal pressure may produce additional stiffening and result in a mass savings. Habitat elements at different pressures would require airlocks between them, resulting in an increased amount of structure, mass and system complexity.

**EVA ACCOMMODATIONS**

- AIRLOCK GAS RECOVERY:

Habitat atmospheric pressure and composition may affect EVA accommodations subsystem hardware and operations in the following ways. Airlock gas losses during depressurization will not be affected by habitat pressure since the final pressure before evacuation is dependent on the depressurization pump technology and not the initial pressure. During normal pressure operations, the airlock and other habitable volumes will leak less gas to the outside environment at lower pressures. Airlock pump mass, volume, and power are not significantly impacted by initial airlock pressure. The airlock pump design is driven by the final pressure before evacuation. Power expended during the initial stages of depressurization is very low compared to the power expended when the airlock pressure reaches low values such as 3.4 – 6.9 kPA (0.5 – 1.0 psia).

- SPACE SUIT SYSTEM MASS AND MOBILITY

A major issue that strongly affects the overall weight, design, and mobility functions of future space suit systems is the pressure level and atmospheric composition chosen for operational use. From both test and functional experience, EVA crew task productivity can be shown to be related to the space suit operational pressure levels. This is especially noticeable by suited subjects with pressurized gloves and corresponding levels of reduced mobility and increased hand fatigue. Higher suit pressure also tends to drive the requirement for increased structural thickness and associated hardware weight increases. The most straightforward method of increasing crewmember productivity and decreasing fatigue is to lower the suit pressure. In general, from an EVA standpoint, suit pressure should be selected from a range of 26.2 kPa – 29.7 kPa (3.8 psia – 4.3 psia). Within this range, current space suit technology yields excellent body and hand mobility and dexterity capabilities and enables a high degree of productivity. Also, within this operational pressure range, the crewmember has a good breathing atmosphere for performing various work loads and is suitable for ventilation and cooling purposes.

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# APPENDIX C – Waste (Joshi)

The following tables contain the details of each waste component.

## A. HUMAN COMPONENT

| | | KG/Person-Day | LB/Person-Day |
|---|---|---|---|
| (Dry) | | | |
| Feces | | 0.03 | 0.07 |
| Urine | | 0.06 | 0.13 |
| Shower/Hand Wash | | 0.01 | 0.02 |
| Sweat | | 0.02 | 0.04 |
| | Total | 0.12 | 0.26 |

## B. INEDIBLE PLANT BIOMASS (DRY WEIGHT)

| | | | |
|---|---|---|---|
| Protein | | 0.25 | 0.56 |
| Carbohydrate | | 0.29 | 0.64 |
| Lipids | | 0.07 | 0.16 |
| Fiber | | 1.09 | 2.41 |
| Lignin | | 0.11 | 0.24 |
| | Total (8) | 1.82 | 4.01 |

## C. TRASH

| | | | |
|---|---|---|---|
| Clothes/Towels | | 0.0007 | 0.0015 |
| Toilet Paper (4) | | 0.0230 | 0.0507 |
| Pads/Tampons (4) | | 0.0035 | 0.0077 |
| Menstrual Solids (4) | | 0.0004 | 0.0009 |
| Paper (4) | | 0.0650 | 0.1433 |
| | Total | 0.0926 | 0.2041 |
| Packaging Material (9) | | | |
| Snack Packaging | | 0.060 | 0.132 |
| Food Containers (5) | | 0.470 | 1.036 |
| Plastic Bags (5) | | 0.060 | 0.132 |
| Food Remains (6) | | 0.100 | 0.220 |
| Frozen | | 0.050 | 0.110 |
| Refrigerated | | 0.020 | 0.044 |
| Ambient | | 0.410 | 0.904 |
| Beverage (10) | | 0.128 | 0.282 |
| Straws | | 0.020 | 0.044 |
| | Total | 1.318 | 2.906 |
| Paper | | | |
| Wipes | | 0.14 | 0.309 |
| Tissues | | 0.02 | 0.044 |
| Facial Tissues | | 0.03 | 0.066 |
| Waste | | 0.004 | 0.009 |
| | Total | 0.194 | 0.428 |
| Tape | | | |
| Masking | | 0.002 | 0.004 |
| Conduit | | 0.004 | 0.009 |

| | | | |
|---|---|---|---|
| Duct | | 0.035 | 0.077 |
| | Total | 0.041 | 0.090 |
| Filters | | | |
| Air (12) | | 0.0244 | .054 |
| Prefilters | | 0.03 | 0.066 |
| | Total | 0.0544 | .120 |
| Miscellaneous | | | |
| Teflon | | 0.011 | 0.024 |
| PVC | | 0.0005 | 0.001 |
| | Total | 0.0115 | 0.025 |

NOTES

(1)Shower/Hand Wash soap = 10g/person-day
(2) Clothes Wash =25 g/person-day
(3) Hygiene latent water (0.43), food preparation latent water(0.03), and laundry latent water (0.06 kg/person-day)
(4) Cellulosic
(5) Polyethylene
(6) 25% protein, 51% carbohydrate, 8% lipid, 16% fiber
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(10 Grounds, P.,"Beverage Pouches",NASA TM SP4-91-081, June 4,1991.
(11) ECLSS Architecture Description Document, Volume 2, Book 2, Revision A , ISS Air filters (2.15 Kg), 29 total

Inedible biomass calculation - Based on 20-day diet using all crops (BVAD)

| Crop | Average Consumption [KG/person-day] | Harvest Index | Inedible Biomass [KG/person-day] |
|---|---|---|---|
| Soybean | 0.086 | 0.37 | 0.146 |
| Wheat | 0.24 | 0.4 | 0.360 |
| White Potato | 0.2 | 0.7 | 0.086 |
| Sweet Potato | 0.2 | 0.7 | 0.086 |
| Rice | 0.029 | 0.4 | 0.044 |
| Peanut | 0.013 | 0.27 | 0.035 |
| Tomato | 0.22 | 0.48 | 0.238 |
| Carrot | 0.041 | 0.9 | 0.005 |
| Cabbage | 0.0038 | 0.9 | 0.000 |
| Lettuce | 0.024 | 0.95 | 0.001 |
| Dry Bean | 0.013 | 0.37 | 0.022 |
| Celery | 0.013 | 0.7 | 0.006 |
| Green Onion | 0.048 | 0.5 | 0.048 |
| Strawberry | 0.016 | 0.4 | 0.024 |
| Peppers | 0.049 | 0.4 | 0.074 |
| Pea | 0.0075 | 0.37 | 0.013 |
| Mushroom | 0.0011 | 0.5 | 0.001 |
| Snap Bean | 0.01 | 0.37 | 0.017 |
| Spinach | 0.04 | 0.8 | 0.010 |
| Crop Sub Total | 1.2544 | | 1.215 |
| Resupplied Food Stuffs | 0.37 | | 0.037 |
| Total | 1.62 | | 1.25 |
| | Inedible Biomass ratio = | 0.77 | |

Inedible biomass calculation - Based on 20-day diet using Carbohydrate crops (BVAD)

| Crop | Average Consumption [KG/person-day] | Harvest Index | Inedible Biomass [KG/person-day] |
|---|---|---|---|
| Soybean | | 0.37 | 0.000 |
| Wheat | 0.22 | 0.4 | 0.330 |
| White Potato | 0.17 | 0.7 | 0.073 |
| Sweet Potato | 0.18 | 0.7 | 0.077 |
| Rice | 0 | 0.4 | 0.000 |
| Peanut | 0 | 0.27 | 0.000 |
| Tomato | 0.21 | 0.48 | 0.228 |
| Carrot | 0.04 | 0.9 | 0.004 |
| Cabbage | 0.0025 | 0.9 | 0.000 |
| Lettuce | 0.021 | 0.95 | 0.001 |
| Dry Bean | 0.013 | 0.37 | 0.022 |
| Celery | 0.0075 | 0.7 | 0.003 |
| Green Onion | 0.034 | 0.5 | 0.034 |
| Strawberry | 0 | 0.4 | 0.000 |
| Peppers | 0.031 | 0.4 | 0.047 |
| Pea | 0.0038 | 0.37 | 0.006 |
| Mushroom | 0.0013 | 0.5 | 0.001 |
| Snap Bean | 0.01 | 0.37 | 0.017 |
| Spinach | 0.04 | 0.8 | 0.010 |
| | | | |
| Crop Sub Total | 0.9841 | | 0.854 |
| | | | |
| Resupplied Food Stuffs | 0.5 | | 0.05 |
| | | | |
| Total | 1.48 | | 0.90 |
| | Inedible Biomass ratio = | 0.61 | |

# APPENDIX D - Psychosocial Interaction Factors (Rudisill)

Background

Even though 40 years of manned spaceflight has significantly increased crew safety and enhanced our knowledge of human adaptation to the space environment, crewed missions remain inherently dangerous. By its nature, space exploration adds significant dimensions to human spaceflight -- long durations in microgravity (including potential monotony during "cruise"), extended distances from the "home" planet (and from primary social and work relationships), isolation and confinement, crew autonomy, non-realtime communications, increased exposure to the physical environment (especially radiation), and decreased perceptual stimulation. All of these factors work together to significantly increase the dangers involved and to potentially decrease crew performance and increase mission risk.

Understandably, during early spaceflight, NASA focused on biomedical and physiological concerns -- keeping the crew "alive and well" and returning them safely to Earth. Once these issues were reasonably addressed, we focused on supporting crew performance with increasing distances (i.e., Apollo) and during increasingly long durations (i.e., Skylab). With Shuttle, we focused on enabling crew habitability and performance on regular missions in LEO. With the Shuttle-Mir and ISS Programs, we are gaining experience with, and insights into, crew issues with regard to regular deployments for "long" durations (i.e., ~three months), albeit in LEO. Clearly, the next step involves moving human crews to significant distances beyond LEO and for missions of significant duration.

We know little about humans "living and working" in space beyond LEO for long durations. However, there are a number of Earth-based analogues to human space exploration -- for example, nuclear submarine deployments, Antarctic missions, naval research vessels, deep ocean oil rigs, undersea science teams -- to aid us in identifying and addressing issues with regard to crew performance on exploration missions (although it must be noted that space missions are more isolated, confined, difficult physical environment, and high risk… than any Earth analogue). These analogues have shown that increased isolation and confinement typically result in increased crew psychological and social problems, such as sleep disturbances, depression, headaches, and crew interpersonal conflicts (including aggressive encounters). The ISS can also serve as testbed for long-duration missions.

Psychosocial Issues

(1) Crew Performance
There are a number of characteristics associated with long duration missions that could compromise crew performance. It is important to maintain appropriate levels of crew performance, especially with regard to safety and mission integrity. Crew performance issues relate to weightlessness, sleep deprivation, sleep-wake cycles, work schedules, isolation, and confinement. Effective crew performance training and assessment tools and methods must be identified, and effective crew work schedules be developed.

Typical astronaut performance on a long-duration mission would involve such activities as controlling and maintaining the spacecraft, performing multiple communications, operating and maintaining onboard systems, conducting scientific experiments, EVAs, and maintaining individual crew health. Crew performance will need to be assessed prior to the mission (by use of discrete and multiple task methods and both partial and full mission simulation). Some consideration should be given to in-flight training/skills maintenance and performance assessment during the long enroute "cruise' portion of the mission.

Astronaut work schedules have occasionally been problematic, especially on long duration missions (e.g., Skylab, Mir) and, in particular, with regard to interactions with ground personnel (e.g., mission control). Some characteristics of long-duration space missions have the potential to significantly disrupt crew performance. Long- term weightlessness may decrease psychomotor skills. Crew workstation designs need to accommodate the neutral body posture and physical changes achieved under weightless conditions so that crew skills are not compromised. Metabolic costs associated with performing EVA tasks need to be managed. Biomedical changes (e.g., diminished cardiovascular capability and biomechanical strength) brought about by microgravity must be considered in crew workload. Space Adaptation Syndrome (SAS) would be expected to occur early on in the mission and would most likely diminish over mission duration; consideration should be given to allowing crew adaptation in LEO prior to departing for a long mission in deep space and, of course, experienced astronauts should be used, thereby reducing the likelihood of SAS episodes.

Standard ISS-like duty schedules should be used (with regular personal time and days free from work), understanding that the crew would most likely be required to devote additional hours to spacecraft and system maintenance given the duration and arduous nature of an exploration mission. Standard times for communications should be established and crew onboard schedules should map to ground control schedules as much as possible. Crew workload needs to be managed and balanced. On an exploration-class mission, it would be easy for crew workload to become excessive. High workload can be maintained for short periods of time, but should not be maintained for any significant duration; excessive crew workload results in stress, fatigue, attention deficits (decreased vigilance and monitoring), and decreased motivation. Interestingly, crew performance decrements are found with both work underload and work overload; therefore, work needs to be structured to maintain crew proficiency and interest, without over- or under-loading. In addition, there should be flexibility in the work schedule (for example, allowing the crew to re-sequence tasks if warranted by onboard conditions), and the onboard crew should have authority to determine their work schedules. Consideration should be given to rotating crew duties to decrease boredom.

Disrupting normal sleep-wake cycles and circadian rhythms (desynchronosis) could have significant negative consequences for crew performance. Concentration, vigilance, decision-making, motivation, and skilled performance decrease with even moderate sleep and circadian rhythm disruption. Desynchronosis problems have occurred on a number of space missions. Space-based zeitgebers (external physical, temporal, and social “cues” that regulate circadian rhythms) should be provided to regulate crew internal clocks, especially given the nature of zeitgebers in space (e.g., no regular day/night cycle).

Sleep disturbances have often been reported in confined environments, such as nuclear submarines and Antarctica, and during space missions. These disturbances have primarily been insomnia and decreased sleep quality (e.g., decreased REM sleep), causing extreme fatigue and depression. Sleep disruptions were also reported during re-adaptation to the 1-g environment upon returning from space missions.

Spacecraft design (e.g., noise, vibration, illumination), habitability (e.g., private crew sleep areas), operations (e.g., sleep disruptive communications with MCC), and work cycle design should, to the greatest degree possible, support “normal” sleep periods and prevent disruption of circadian rhythms (e.g., no staggered sleep schedules or multiple shifts).

(2) <u>Crew Interactions</u>
Crew interactions relate to issues associated with overall crew functioning and compatibility, including individual characteristics, gender, age, culture, competence, and leadership.

It has always been the case that career astronauts are highly intelligent, educated, self-motivated, physically and mentally healthy individuals, having personality characteristics that lend themselves to high probability of mission success. Understandably, the crew selection focus has not been on choosing individuals whose strengths lie in interpersonal skills and high degrees of team cooperation, but on technical skills and competence. Also, selection of members for a specific mission has not rested on choosing highly compatible individuals, but on selecting those individuals with the right mix of skills and talents. Interestingly, it has been noted (via personal communication) that formation of a crew from individual astronauts has happened by serendipity. Crewmembers move into the same office once assigned to a mission and train together for several months prior to the mission; any interpersonal difficulties have typically been solved prior to the mission. Exploration missions will require a high degree of group cohesion and co-operation and strong interpersonal skills (given the requirement to live and work together in a small confined environment for a long duration); therefore, more emphasis will need to be placed on individual crew personality characteristics in selecting exploration crews.

<u>Crew Size</u>
In addition to its impact on vehicle, crew size primarily affects the amount and types of mission work that can be accomplished; when selecting the number of crew, consider skills required, cross-training capabilities, and underload/overload over the mission duration. While crewmembers should not be required to work at the limits of their abilities and skills for the mission duration, . It’s recognized that

design and mission operations are the primary crew size drivers, but consideration should also be given to safety and the number of social relationships/conflicts afforded by particular numbers of individuals.

Gender

With regard to mixed-gender exploration crews, since men and women have worked side-by-side in multiple space missions, including long duration missions on Mir and ISS, with no problems, it is expected that there would be no problems associated with a mixed-gender crew on exploration missions. In fact, the inclusion of women in previously all-male analogue environments, such as Antarctica and research vessels, had a positive "moderating" effect (e.g., in terms of decreasing the number of aggressive episodes). Some consideration needs to be given to the number of crew and the number of men or women. Also, existing flight rules prohibiting including married astronauts on the same crew should be reviewed.

Age

It is also expected that exploration crewmembers would be somewhat experienced astronauts; hence, they would most likely be in their 40's or older. It is not expected that there would be any issues associated with mixed age crews on exploration missions.

Culture

To date, there have been a number of multicultural crews on Shuttle and Mir missions and this, of course, is continuing on the ISS. At times, special provisions have been made to accommodate the special cultural requirements of particular crewmembers (e.g., special foods). It has typically been the case that, even though individual astronauts may come from different national cultural backgrounds, their similarities have outweighed their dissimilarities. That is, astronauts are selected from special groups within populations and, therefore, have generally had more in common (e.g., education, training, motivation) than not. Therefore, although multicultural crews may appear culturally diverse "on the outside," the individuals have found common ground and forged a cohesive crew.

Nonetheless, a deep space human exploration mission may very well be international (for cost-sharing purposes) and, therefore, the crew would most likely come from multiple cultures. Long durations in isolation and confinement can prove difficult for members of the same culture; such mission circumstances could potentially be very difficult with a very culturally diverse crew.

To reduce cultural-based mission risk, a number of operations rules should be investigated and established. It is important that all astronauts, regardless of national or cultural background, perform mission training together and to the same level for a duration allowing for cultural differences to be addressed prior to departure. It is inappropriate that one single culture (e.g., U.S.-based) be "imposed on" all crewmembers; other cultures and national views can be acknowledged without undermining the nature of an exploration mission. All crewmembers should have equal status (based upon crew position) regardless of national origin (i.e., no "guest" status crew). For operations effectiveness and safety, a single "mission" language should be chosen (as on ISS) and all crewmembers should have equal language proficiency. Accommodation should be made for culturally diverse foods. The "national political nature" of an exploration mission (and the crewmembers as representatives of those nations) should be acknowledged, but training and public communications should foster crew cooperation and pursuit of common goals. In effect, an international crew would represent, as an entity, the entire "home planet," not only their individual nations.

Crew Selection Characteristics

Selection of crewmembers should focus on individual characteristics that lend themselves to group cohesiveness and cooperation. In addition to high competence, crewmembers should have a strong "task orientation"; a high degree of perceived competence and task focus has correlated positively with team cohesiveness and mission accomplishment in analogues (e.g., Antarctic). Individuals should have a clear "joint-gain/team player" motivation (i.e., cooperative actions benefit the entire team) rather than "own gain" or "relative gain" motivations. Crewmembers should demonstrate strong social and interpersonal abilities. They should also be balanced in introversion (internal, analytical focus) and extroversion (external, social focus) traits -- in effect, flexible "ambi-verts" who are equally comfortable with both the rigors of confinement/isolation and multiple social interactions. Research needs to address the issue of degree of homogeneous attitudes and values required across the crew to mitigate intra-crew conflicts. Individual crewmembers should be selected to provide complementary skills across the entire crew.

Particular attention must be paid to selecting the individual to lead a first space exploration mission. Unquestionably, leaders direct and coordinate the efforts of team members across all aspects of mission conduct, but they also are in a position to influence group goals, cohesion, and stability and to resolve crew interpersonal conflicts. In effect, the crew leader can serve as a primary focus to ensure mission accomplishment under the rigorous characteristics of an exploration mission. Therefore, the leader of a space expeditionary force must have both strong leadership abilities and superior interpersonal skills. Research on leadership in isolated, confined environments suggests that a mature, competent, experienced individual is perceived as a stronger leader than an "action-oriented" individual.

Crew Team Performance

As one can examine individual crewmember performance on an exploration mission, one can also identify issues associated with performance of the entire crew team. A number of factors affect crew team performance. Example factors include: the knowledge, skills, attitudes, motivation, performance strategies, and personality characteristics individual members bring to the team; group factors, such as size, cohesiveness, and leadership; and environmental factors, such as mission tasks and risks. Team performance can be enhanced through operations and design choices, such as group composition, individual commitment, and crew physical and psychological well-being. The cohesiveness or "unity" of an exploration team could be aided by identifying clear group goals and by fostering individual commitment and cooperation. Methods for training the crew to identify and manage conflicts and stress during the mission are also required.

There are also crew team issues that could undermine the mission and safety of an exploration crew. When confronted with a threatening or unsafe condition, an exploration crew would be particularly vulnerable to "groupthink" (where maintaining group harmony prevents critical thinking, leading to poor or unsafe decisions) because of their restricted communications outside the team and perceived need to support group cohesion. A second circumstance occurs during emergency situations where the leader, in making a decision, makes a mistake (e.g., misinterprets instrument information) and individual crewmembers do not behave assertively to correct the error or question the decision. Crew team training needs to be developed to aid the crew recognizing and preventing these types of group performance deficits.

The crew team also develops over the duration of the mission; this is seen in shorter missions, such as Shuttle and on ISS, and would be more pronounced on long-duration missions. Early crew behaviors focus on forming a cohesive team, defining the leader/subordinate roles and responsibilities, and establishing team norms; later, the team focuses on performing the mission tasks; when the primary mission tasks are accomplished (e.g., collecting samples from the Martian surface), the team focus is directed to returning home and re-establishing their lives. One related issue is that team cohesion needs to be maintained over the long duration of an exploration program, that is, through the multiple years of training, the actual mission, and return. Crew training needs to be developed to foster these types of team-building activities. In addition, early exploration team building would occur during training, providing an opportunity to observe and foster the process prior to departure.

(3) Communications

The primary purposes of communications are to provide both the crew and mission control mission-specific information required to accomplish the mission and to provide the crew with secure access to their loved ones at home and for medical discussion purposes. There are special issues with regard to communications, driven by the isolation, confinement, and distances associated with deep space exploration. Distance would prevent simultaneous communications (with a maximum roundtrip time between Earth and Mars of approximately 20 minutes), so procedures are required for regularly communicating important information "non-simultaneously" (e.g., regular, periodic computer-to-computer transmissions; regularly scheduled crew videos sent to Earth for public dissemination).

Within the spacecraft environment, direct crewmember-to-crewmember communication is altered and will need to be considered during spacecraft design. Weightlessness and the artificial atmosphere alter the human vocal apparatus, changing voice quality and, hence, speech communication. Nonverbal "paralanguage" cues are also modified – redistribution of water alters facial expressions and changed gestures and body position together reduce communication. Noise (primarily from fans constantly circulating the atmosphere) requires that crew wear communications headsets (a problem in itself) and raise their voices to be heard over short intra-vehicular distances.

Language difficulties are not expected. As was noted earlier, all crewmembers will have high competency in the official mission language and will also share a common "technical" language, so there should be few communications problems caused by these factors.

On space missions presently, the majority of communications are "mediated" through an electronic medium. Given the special circumstances associated with an exploration mission (especially communication time delays), it is expected that electronic communication will take on added significance. Communications should include full-motion video, audio, and computer-based modes. Research has shown that there are specific advantages and disadvantages associated with "mediated" communication that will need to be considered during design. For example, electronic communication forms work well for routine, formal, simple, structured, non-simultaneous information sharing but are less effective for messages required interactivity and having a social or emotional aspect (e.g., speaking with one's spouse and children over a long distance).

Technical issues with communications

- Video

Transmitting video quality pictures and movies is dependent upon the size, quality and intent of the video. Typically, transmission of decent resolution video pictures and graphics requires high data rates associated with communications to/from Earth. This usually results in the need for more powerful and sizeable communications systems. The further the distance from Earth for the mission, the more robust the communication systems have to be to overcome the large distances. This "robustness" typically affects the spacecraft power, mass, sizing and operations considerations. New techniques in video compression need to advance to provide error-free transmission of "TV-like" video quality. Recent advances in optical communications needs further refinement to provide the video needs of future manned missions. Some over-the-horizon research is required to determine if recent experiments on Earth of faster-than-the-speed-of-light transmissions have merit for Deep Space communications. Achieving any advances in reducing data transmission delays would be a significant benefit for any mission, but most importantly for a manned mission.

- Audio

Transmitting audio and sound places fewer demands upon the communications system than video, and typically takes far less data bandwidth than the needs of a video link. However, if manned missions are trying to provide a video with audio, then communications design is required to synchronize the audio to the video transmission. Although systems already exist to provide this capability, more advanced designs will be necessary to accommodate missions to Mars and beyond.

- Computer-to-computer (e.g., email, burst, text, graphics)

If outbound manned missions generate large amounts of science and engineering data, there may have to be considerations for how often that data is desired to be relayed back to Earth (and vice versa). Providing a more autonomous communications system is important during long duration manned missions.

With regard to task-oriented communications between crew and MCC, in addition to problems exacerbated by time delays, the quality or character of the exchange is also affected. Through the history of the space program there have been a number of communications-related incidents between crew and ground. Many of these crew-ground difficulties have arisen from excessive crew workload and crew perception of excessive demands from ground personnel, including issues of authority in determining task priorities. Studies of communications during isolation and confinement have shown that crew frustration (and resulting "hostility") is directed toward ground personnel; in the Russian space program, it is recommended that ground controllers receive training in interpersonal relations, given the major role they play in regular interactions with the crew.

Within the space program, a formal, structured communications protocol has been created to address some of these problems (e.g., all interchanges with the onboard crew are conducted through a single ground-based person who is also an astronaut). A challenge for an exploration mission is to design a method for crew-ground communications that will allow regular ground access to the crew without, simultaneously, being constantly intrusive or interfering with onboard operations. Although technically feasible, it is inappropriate that a communications system would allow ground personnel to access the crew at will, essentially “unannounced.” The single point of contact between crew and ground should be maintained. Procedures and protocols for managing crew/ground communications under the special circumstances associated with deep space exploration should be developed. Given a high crew mission workload and the added stressors associated with long duration isolation and confinement, it is particularly important that the crew be provided with the information they require to perform the mission, and that inessential information be limited to reduce distractions.

The exploration crew must be provided with regular, secure communications with their families, with communication opportunities distributed equally across the entire crew at regularly scheduled times. This is particularly important given the distance and isolated nature of this type of mission. Studies have shown that, under these mission circumstances, the crew will have an increased desire to communicate with those at home and that the communications will increase in duration. Therefore, both the crew and their families must be advised of the need for regular communications and the potential for issues to arise from poor communications. Regular crew/family communications provide the opportunity to reduce anxiety with both communicants and may reduce the need for inter-crew interpersonal interaction. Secure communications must also be provided for the crew to regularly interact with ground-based medical personnel for health maintenance purposes.

Capability must also be provided for regular communications with the public on Earth for public outreach, education, and sharing of the exploration experience. This should include video as well as audio, and perhaps email for addressing specific public questions. Given the time delays involved, there is, at present, no capability for real-time public/crew interaction; therefore, communications will be accomplished “pseudo-realtime.” Earth-based public questions could be provided regularly to the crew through a single source and perhaps crewmembers could address them via video which is then sent to Earth for public viewing.

Crew will also need to communicate regularly with researchers on Earth, especially during surface operations. Again, given the non-realtime nature of the communications, alternative methods for regular interchanges are required. Perhaps researcher communications could be regularly collected and transmitted to the crew through a single science point-of-contact on Earth and a designed science crewmember could have primary responsibility for responding. Consideration should be given to allow direct communications access between a ground-based representative of the “science team” and the onboard science officer.

(4) Emergencies & Crises

It can be expected that there could be unique emergencies or crises that arise from threatening events associated with the characteristics of a deep space exploration mission. Some events could be severe and life-threatening. Emergencies and crises can arise from external events, such as equipment malfunction/failure or an SPE, or from crew-related issues (e.g., an emergency medical problem).

There have been a number of external emergencies and crises, from the Mercury Program (3), Gemini/Apollo (4, including Apollo 13), Skylab (2), Apollo/Soyuz (1), Soyuz (at least 12), through the Shuttle Program. Given the danger inherent in the space environment, it is to be expected that threats, emergencies, and crises will continue to occur. Understandably, individuals respond to external threats with autonomic-based stress reactions, generalized anxiety, fear, and depersonalization, although there is wide variability in individual reactions. Such reactions are adaptive in that they bring to bear the individual’s internal resources to act, but beyond a certain response level the stress reaction impairs performance. Astronauts are, of course, trained to respond effectively to emergency situations; such training can provide skills to reduce a specific threat and can also provide an effective generalized response to threat situations. Cosmonauts are exposed to a series of life-threatening situations to “prepare them psychologically” for potential threats in space; that is, the assumption is that exposure breeds familiarity and enhances performance in the event of a true external threat. Specific coping strategies can also be learned, such as focusing attention on the external threat rather than on the internal subjective reaction which, in turn, enhances performance in reducing the danger. Consideration should be given to identifying and enhancing the astronaut selection criteria to include specific personality characteristics that have been demonstrated to be adaptive to stress and threat situations.

In addition to the individual’s response to a crisis, the entire crew team must respond effectively. A general and predictable reaction is “fear affiliation” in that the entire team pulls together in response to the common external threat. Understandably, the quality of leadership during an emergency determines to a great extent the team's ability to resolve the threat (e.g., by formulating and coordinating the responses of individuals) and return to normal functioning. Training programs should be enhanced to deliberately expose an exploration crew to threat situations. Team procedures to deal with specific threat situations should be defined and well trained. Leadership behavior during a crisis should be a prime consideration when selecting the mission commander.

There is also the possibility of a threat imposed internally from an individual crewmember, which could have a serious effect on the mission. Confinement situations have been shown to increase psychological disturbances in a number of space analogues, such as Antarctic missions and nuclear submarine deployments. These have primarily been mood disturbances such as depression, sleep disruption, and chronic headache. Some may be generalized stress responses resulting from a failure of the individual to adapt to the difficult environment or the lack of social support during adaptation. The type of response is often related to individual methods of situational coping (e.g., withdrawal vs. humor). Although isolation, confinement, and monotony can contribute to depression, generally it is negative life events (e.g., divorce, a child's severe illness) that can trigger a psychological episode in even the healthiest individual.

One particular life event, the death of a loved one, produces grief and may be experienced by an individual crewmember as a profound sense of loss, especially if the death is unexpected. (Whereas bereavement or mourning refers to the cultural customs associated with death, grief is experienced as a physiological response.) The affected crewmember could have a particularly negative response to this event, given the inability to intervene or be present to help their family deal with the loss. Grief can be a serious stressor, potentially causing depression, sleep disturbance, appetite loss, breathing difficulties, apathy, and withdrawal. Unfortunately, grief appears to be essential to recovery from the loss. It is not clear how a crewmember could be helped through this event from such a distance; with little "opportunity to recover" in situ, it is unclear how the crewmember's performance would be affected. NASA must determine when and how events on Earth should be communicated to an exploration team member, who is obviously helpless to aid the situation at home.

A strong defense against these types of individual crises is, of course, initial selection for the astronaut corps, later selection as an exploration mission team member, and preparatory training. For example, the U.S. Navy has identified special individual personality characteristics associated with selecting crew for submarine duty (it should also be noted that the Navy also provides additional clinical psychology training to the onboard medical office, and there have still been a number of debilitating psychological incidents with crew). Generally, NASA's approach in psychological assessment has been to reliably "select out" unfit individuals. NASA should consider enhancing the psychological assessment portion of the astronaut candidate evaluation to deliberately "select in" individuals exhibiting specific positive attributes (clearly a more difficult choice). Selecting the highly goal-oriented, motivated, self-directed, high achiever may continue to be the best choice, but this individual must also be capable of effectively dealing with possible failures and difficulties which a long-duration mission would impose on the exploration crew.

A related question involves how to treat a crewmember exhibiting signs of psychological upset. Consideration should be given to training the entire crew, to raise their awareness of possible problems they or their fellow crewmembers may experience. The mission commander should receive additional training to enable him or her to assess crew behavior. The medical officer should receive focused training in psychological intervention and countermeasures. The families of crewmembers should also receive training to increase their sensitivity to issues that can occur during the mission and also receive support and counseling during the mission. A great deal of the responsibilities and, therefore, the stress, will be borne by those the crew leave on Earth when they depart. Crewmembers could also be trained in meditation, relaxation, and biofeedback methods which have been demonstrated to serve as generalized stress reducers; a well-designed regular exercise program can also reduce stress and enhance well-being. The overall goal is preventing an episode by recognizing potential problems early on and intervening in effective ways. Treatment countermeasures and procedures need to be defined prior to the mission. Gainful work and onboard training can be used to provide a structured environment and to focus one's attention. (Note: Substance abuse, primarily with alcohol, has been a precipitating factor in a number of psychological episodes in space analogues; it is expected that the present "no alcohol" policy will be maintained on exploration missions.)

A final crisis involves the death of a crewmember aboard the spacecraft, whether by a medical emergency or a mission event, such as an equipment failure during an EVA. Undeniably, this would have a profound effect on the crew. The remaining crew would be required to deal with both the psychological (i.e., emotional) and physical (i.e., handling the body) demands of the event. Clearly, procedures and vehicle design for managing such a crisis must be considered prior to sending an exploration mission. Perhaps exploring how these events were handled by ships at sea, the Navy's present rules concerning death on deployed submarines, and the death of an individual in the Antarctic during a winter-over where there is no rescue for several months, could provide some guidance.

(5) Crew Structure & Authority

Although mission planners and operations personnel design the exploration mission and supporting vehicles, it is the crew that operates within the designed system and, therefore, the crew should be directly involved in formulating mission plans. This ensures that crewmembers' skills and needs are directly considered in the mission. One issue related to mission design is the organizational structure of the crew. Crew organization defines the structural and authority relationships within the crew and between the crew and other organizations.

Organizational Structure

The most common organizational structure, and the structure typically used on space missions, is multilevel hierarchical or pyramidal. Leadership within this structure tends to be formalized with formal supporting role relationships. In this type of structure, leadership follows from perceived competence; the crew must have total confidence in the commander's expertise. Note, however, that under long-duration mission conditions, perceived leadership authority based on expertise may be eroded to the degree to which others are cross-trained in the commander's areas of expertise.

Unquestionably, the leader of a hierarchical organization must be perceived as a full member of the group – that is, as "one of us" – by members of the team. For both experience and leadership reasons, the mission commander will be selected from the ranks of experienced astronauts; consideration should be given to allowing potential crewmembers to nominate mission commanders from their ranks.

Authority

Space missions have primarily been highly interactive, with authority shared between mission control-based personnel and the onboard crew. However, the long distances associated with exploration missions may make this difficult, so for these types of missions, NASA should move to increase onboard centralization of authority and crew autonomy. The commander's knowledge of local conditions will significantly enhance the crew's ability to respond to mission demands. Centralizing authority onboard also prepares the commander's support personnel to share decision-making responsibilities. Ground personnel should focus on addressing long-range issues. This arrangement can work well if the crew and ground maintain good communications (see the Communications section) and if personnel can regularly access an array of staff specialists to support decision-making. An alternative to the purely hierarchical crew organizational structure is one based on a "labor relations" model, where centralized authority and group member participation are blended. The leader is the final decision-making authority, but team members participate by actively providing information and their perspectives. A crew and authority definition needs to be defined for exploration missions. These organizational issues, as well as crew size, the nature of the crew, the mission, and communication system, need to be considered.

Work Roles

The types of work roles that crewmembers fulfill also influence crew structure. There are generally four functional crewmember work role groups that relate to the primary tasks performed within group positions. The first work role group concerns performance of flight operations tasks, where participants perform tasks such as mission command; guidance and navigation; flight engineering; vehicle systems monitoring and control; and communications. These roles have been primary in space missions since its inception. Note that the space mission commander position has traditionally been drawn from this group, but this may not be necessary. Other skills, such as organizational management and interpersonal interactions, may be emphasized.

The second crew work role group focuses on the scientific investigative function and primarily involves performing research tasks. The focus is on collecting data related to scientific questions, performing analyses, and addressing scientific questions related to the mission. Although scientific tasks are not essential to the mission, they often serve as the primary justification; it is expected that science will be a primary focus on exploration missions.

Spacecraft environmental support roles include tasks associated with maintaining the vehicle and habitable environment, such as managing logistics and supplies. With a small crew, these roles can be combined with flight operations responsibilities. The final group involves personnel support crew tasks involved in maintaining the health of the crew, such as the medical officer.

Crew roles and responsibilities across these groups should be evaluated and defined specifically for exploration missions. A number of factors should be considered when defining these crew roles. Commonality across positions where a crewmember could serve multiple roles or functions should be addressed. When combining crew roles, care should be taken to prevent overload across tasks. Distributing tasks and responsibilities across crew should ensure that each crewmember is contributing equally to the entire crew team. Tasks should be defined and distributed such that crew individual and team motivation is maintained during the duration of the mission. Mission work must be intrinsically rewarding (e.g., accomplishing a scientific objective; expanding human presence; representing humanity), especially since typical extrinsic rewards (e.g., money) are back on Earth and the crew is operating under conditions of extreme risk.

Organizational Conflicts

During long duration exploration missions, there is the possibility of conflict across organizations, particularly between crew and mission control. Communication across organizational interfaces is typically served by a set of “boundary” positions; in the space program, these functions are performed by astronauts and selected mission control personnel. Persons in boundary role positions not only provide information to the organizations served (e.g., crew and mission control), but also influence organizational behavior (e.g., negotiating task performance with the crew). Understandably, the quality of the relationship between the crew and organizations on Earth will be determined by those serving as the interface between them. It is, therefore, important that personnel in these special positions understand their role in maintaining smooth working relationships among the mission organizations.

One noteworthy example of crew/mission control conflict arose on the Skylab 4 mission, although there is variability in interpreting these events. There was an initial factor of hiding a crewmember’s motion sickness. The commander decided not to inform mission control, which eventually determined the problem and reversed the commander’s decision (a mitigating factor may have been the question of authority). The crew made several negative and critical comments with regard to Skylab living conditions, but these comments were provided in response to a habitability questionnaire. However, a major issue concerned crew workload. Mission controllers had overloaded the crew’s schedule with tasks; in response, the commander placed a “hold’ on crew activities for one day while the crew schedule was re-worked on the ground. It is generally accepted that the Skylab 4 crew was under a great deal of work pressure; they maintained an overloaded schedule for a while, but over the three-month mission duration the excessive workload caused stress. A number of conflicts arose between the crew and mission control, where the crew’s frustrations with workload, illness, authority, and difficult living conditions were translated into frustration that was regularly directed at mission controllers.

For exploration missions, care must be taken to not “over-program” crew time, crew needs regular time away from work tasks, clean lines of authority must be established prior to the mission, and living conditions must be designed to reduce stress. Rules for conflict management should be defined prior to the mission. Although conflict can serve a positive purpose if it is instrumental in addressing problems and resolving issues, it can have significantly negative consequences on an exploration mission; therefore, persons serving in the “boundary role” positions must be trained in methods to reduce conflict.

(6) Reassimilation on Earth Return

An exploration crew could easily be together for five or more years, through initial selection for the crew, mission training, and the mission proper. It would be expected that, during that time, each crewmember would focus a great deal of time and energy on accomplishing the mission. When the mission is completed and the crew returns to Earth, each individual will need to be re-assimilated into the life he or she left behind.

Studies and military experience have shown that the separation imposed by the mission and the subsequent re-assimilation can be disruptive to the crewmember’s family. During training and the crewmember is away on the mission, the remaining family members must fulfill all of their family needs; the primary responsibility for managing the family rests with the crewmember’s spouse.

The crewmember's spouse had to deal with problems associated with loss of the primary relationship partner. Other forms of close supporting relationships need to be fostered and maintained throughout the entire mission preparation and mission sequence. In addition, the spouse must assume responsibility for all areas of maintaining the family, including responsibilities of parenting. The crewmember, deeply involved in the mission, also must face the difficult issues of guilt associated with missing family occasions and burdening the spouse with additional responsibilities.

After the mission, the crewmember must be re-assimilated into the family. This can be a difficult process, during which the family roles must be re-defined and re-established. Frustration, resentment, and guilt, stored over the mission, can come to the fore and affect the re-assimilation process. Depression resulting from the mission's end can interfere with the happiness associated with returning safely. The spouse who remained behind and managed the family during the mission has established family rules and may feel uncomfortable giving up primary authority and modifying his or her established behaviors. The spouse can also feel unappreciated, by both the crewmember and NASA, for the depth of his or her dedication and responsibility in maintaining the family structure in the crewmember's absence.

These issues need to be addressed for exploration missions. Crewmembers do not exist alone in the world, but have close families, friends, and established interpersonal relationships. Fundamental relationships will be strained significantly by an exploration mission and the people involved need to have support structures in place to help sustain them for the duration of the mission, from planning through crew return. Consideration should also be given to types of familial selection characteristics of an exploration crew. For instance, should crewmembers be married or unmarried? Should married astronauts be considered for the exploration crew? Should crewmembers have young children still at home or not, to lessen the burden on the remaining spouse? These are issues that need to be addressed prior to mounting a deep space, long-duration exploration mission.

(7) Psychological Design

**TBD**

References


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